Applications of Rowing Instrumentation Systems

A thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

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Abstract

The objectives of this thesis were to establish the validity of commercially available rowing instrumentation systems for the measurement of oar angles and power to inform the interpretation of these measures, extend knowledge regarding the prediction of on-water rowing race performance and the contribution of measures of rowing technique and boat acceleration to rowing performance. From a practical perspective, this thesis aims to enable coaches and sport scientists to identify specific areas where performance improvements can be attained in the athletes they work with.

Studies One and Two established the concurrent validity of rowing instrumentation systems for measures of oar and power, respectively. Concurrent validity was acceptable for Peach systems for oar angle (trivial to small but unclear systematic bias, and trivial to small random errors) and power per stroke (possibly or likely trivial random errors of -3.0 to -16%). EmPower systems did not have acceptable validity for oar angle (trivial to small but unclear systematic bias, and moderate to extremely large random errors) or power per stroke (likely or decisively substantial random errors of 9.7 to 57%). Only power was assessed in Weba and Concept2 systems as catch and finish oar angles are not measured by these devices. The random error associated with power per stroke was 61 to 139% for Weba and -28 to 177%) for the Concept2. Systematic bias in mean power was negative for all devices (Concept2, -11 to -15%; Peach, -7.9 to -17%; EmPower, -32 to -48%; Weba, -7.9 to -16%).

Study Three investigated the contributions of power, stroke rate, headwind, technical efficiency, race conditions, and stroke-velocity variability in 45 rowing race performances. The unexplained prediction error was 0.35 to 0.55% across the four boat classes assessed. Effects on race velocity were extremely large for mean race power, small to large for mean stroke rate in singles, large to extremely large for headwind, trivial to extremely large but unclear for technical efficiency, very large or extremely in singles for race conditions, and small to trivial but mostly unclear for stroke-velocity variability.

Specific measures of rowing technique from the Peach system were investigated in Study Four by evaluating their individual relationships with rowing velocity. Substantial relationships with velocity were found between most variables before adjustment for

power and stroke rate, but effect magnitudes were reduced after adjustment for power and stroke rate. The greatest modifying effects were found for stroke rate, mean and peak force, and power output before adjustment, and for catch angle after adjustment for stroke rate and power.

Study Five explored relationships between boat acceleration profile and rowing performance. Several measures of acceleration magnitude and jerk had substantial effects before adjustment but were reduced in size after adjustment for stroke rate and power. Substantial effects were found for maximum negative drive and peak drive acceleration magnitudes, and jerk in the early-to-mid drive and late recovery phases after adjustment for stroke rate and power.

The findings of this thesis show Peach instrumentation systems have adequate reliability for stroke-to-stroke assessment of oar angles and power output. Race performance can be predicted from power, stroke rate and technical efficiency. Stroke rate, power, force, and catch angle are key areas where improvements in performance can be attained, as are changes in boat acceleration profile reflecting the late recovery, catch placement and early drive phases of the stroke.

Student Declaration of Authenticity

I, Ana Christie Holt, declare that the PhD thesis by Publication entitled Applications of Rowing Instrumentation Systems is no more than 80,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references, and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

I have conducted my research in alignment with the Australian Code for the Responsible Conduct of Research and Victoria University's Higher Degree by Research Policy and Procedures.

All research procedures reported in this thesis were approved by the Victoria University Human Research Ethics Committee, approval numbers HRE18-085, HRE19-036, HRE19-014, and HRE19-106.

Signature: Date: December 8th 2021

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Chapter Five

Holt, A. C., Siegel, R., Ball, K., Hopkins, W. G., & Aughey, R. J. (2022). Prediction of 2000-m on-water rowing performance with measures derived from instrumented boats. *Scandinavian Journal of Medicine and Science in Sports, 16*(8).

Holt, A. C., Siegel, R., Aughey, R. J., Hopkins, W. G., & Ball, K. (2020). Differences in boat velocity related to technical efficiency in highly-trained rowers. *International Society of Biomechanics in Sport (ISBS) Proceedings Archive, 38*(1), 220.

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Holt, A. C., Aughey, R. J., Ball, K., Hopkins, W. G., & Siegel, R. (2020). Technical determinants of on-water rowing performance. *Frontiers in Sports and Active Living*, 2, 178.

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Holt, A. C., Ball, K., Siegel, R., Hopkins, W. G., & Aughey, R. J. (2021). Relationships between measures of boat acceleration and performance in rowing, with and without controlling for stroke rate and power output. *PloS one, 16*(8), e0249122.

Chapter One: Introduction

1.1 Background

On-water rowing races are held over 2000-m and comprise 20 different boat classes, including sweep (one oar per rower) and sculling (two oars per rower), with crew numbers ranging from one rower in a single scull up to eight rowers and a coxswain in an eight. Individual rowing performance can also be assessed on indoor rowing ergometers over 2000-m, with distance covered calculated from the power applied by the rower. Numerous factors contribute to rowing performance, of which the absolute measure of success is the time taken to complete 2000-m, and therefore the corresponding average boat velocity (or average power for rowing ergometer performances). Knowledge of the factors contributing to boat velocity and power output, and a valid system for their measurement, is necessary for effective and targeted improvements in rowing performance and the assessment of its progression.

Rowing instrumentation systems enable measurement of the power applied at the oar, stroke rate, force application at the oar’s handle, and the oar angle rowed through, providing a comprehensive assessment of both technical and physical aspects of rowing performance. In practice, rowing instrumentation systems are most commonly used for technical analysis, but also prove valuable for training intensity adherence (Lintmeijer, van Soest, Robbers, Hofmijster, & Beek, 2019). Scope exists for rowing instrumentation systems to be used for performance modelling, and training prescription and monitoring, as they are in cycling. To date, research investigating the validity of rowing instrumentation systems have only assessed the Peach PowerLine system (Peach Innovations, UK), which demonstrates acceptable precision and repeatability for force and static angle measures in laboratory settings (Coker, Hume, & Nolte, 2009; Laschowski & Nolte, 2016). However, the validity of this system and other commercially available rowing instrumentation systems have not been tested in a rowing-specific setting.

Rowing performance not only has high demands on the aerobic and anaerobic systems, but also requires technical proficiency (Riechman, Zoeller, Balasekaran, Goss, & Robertson, 2002; Soper & Hume, 2004c). Power output and stroke rate are important components of on-water rowing performance (Coker, 2010; Kleshnev, 2001; T. P. Martin

& Bernfield, 1980; Mikulić, Smoljanovic, Bojanic, Hannafin, & Matković, 2009). Research investigating measures of rowing technique indicate earlier occurrences of peak force in the stroke, and higher mean-to-peak force ratios during the drive phase to be advantageous (Coker, 2010; R. M. Smith & Draper, 2006; Warmenhoven, Cobley, et al., 2017). However, a number of technical measures have not yet been assessed.

The boat acceleration profile provides a comprehensive illustration of both the net forces and the influence of rowing technique impacting rowing velocity (Kleshnev, 2010a). Visual inspection of acceleration profiles is commonly used to assess force application and technical components of rowing performance, with greater acceleration peaks achieved during the drive found to be advantageous (Kleshnev, 1998, 2010a). Nevertheless, interpretation of boat acceleration profiles is largely based on experiential knowledge, with the limited research available subject to contradictory findings, qualitative measures of performance, small sample sizes, and limited boat classes (Kleshnev, 1998, 2010a; R. M. Smith & Draper, 2006).

Given the limitations identified in the literature review process, further research is needed to establish the relationship with on-water performance for the measures of rowing technique provided by rowing instrumentation systems, and those for the boat acceleration profile, across a range of boat classes. Such research would extend the current knowledge regarding the contribution of rowing technique to overall performance and inform measures of technical assessment related to performance improvements. Additionally, investigation of the demands of on-water performance would enable the identification of crew-specific strengths and weaknesses, consequently directing the training focus. However, the validity of rowing instrumentation systems in an on-water rowing specific setting must first be established.

1.2 Study Aims

The overarching objective of this thesis is to extend the current knowledge regarding the validity of commercially available rowing instrumentation systems for the measurement of oar angles and power, informing the observation of meaningful change in these variables by practitioners and their use in identifying factors contributing to rowing performance. Additionally, this thesis sought to understand the contribution of measures of rowing technique and boat acceleration to rowing performance to better equip coaches and sport scientist in identifying areas where improvements in performance can be achieved. The aims of the respective studies presented in this thesis are therefore to:

1. Assess the validity of oar angles measurement from Peach PowerLine and Nielsen-Kellerman EmPower sweep rowing instrumentation systems.

2. Evaluate the validity of power output measurement from Peach PowerLine, Nielsen-Kellerman EmPower, and Weba Sport OarPowerMeter sweep rowing instrumentation systems.

3. Predict 2000-m on-water rowing race performance by determining the contributions to average race velocity of power output, stroke rate, technical efficiency, and environmental conditions.

4. Investigate the effects of biomechanical measures of rowing technique on rowing performance in race conditions.

5. Establish relationships between boat acceleration profile and rowing performance in race conditions.

1.3 Thesis Organisation

This doctoral thesis examines the validity of instrumentation systems in rowing, and their use in establishing the factors contributing to rowing performance. This thesis adheres to a standard format for a Doctor of Philosophy thesis, as recognised by Victoria University. The sections in this thesis include an introduction, literature review, five research chapters, an overall discussion, reference list, and appendices.

Specifically, Chapter One includes the introduction, which provides context and presents an overview of the thesis. Chapter Two incorporates a literature review, which introduces the reader to current measurement practices for the assessment of rowing performance. The literature review involves evaluation of the measurement of boat velocity, rowing ergometer performance, and methods of technical analysis, before introducing the use of rowing instrumentation systems and what is currently known with regard to their validity in rowing, and how they have been used in other sports. Critical analysis of the research conducted in the areas of rowing instrumentation system validity and technical contributions to rowing performance provide justification for the research conducted in this thesis.

Chapter Three presents the first research chapter, which investigates the concurrent validity of two commercially available instrumentation systems, Peach PowerLine and Nielsen-Kellerman EmPower devices, against a Vicon motion analysis system for their measurement of catch, finish and arc angles in rowing throughout a range of stroke rates. The findings of this study are expanded on in Chapter Four, which evaluates the concurrent validity of power from Peach and EmPower devices, with the addition of Weba OarPower Meter and Concept2 Model D devices (which do not measure catch and finish oar angles so were not included in the previous study), against an instrumented rowing ergometer system for their measurement of power output. The device bias established in Chapters Three and Four inform the interpretation of results in the following three chapters.

Chapter Five assesses the contributions of power output, stroke rate, rowing efficiency related to technique, environmental conditions, and the variability in velocity between-strokes to overall 2000-m race performance, and explores the prediction of race performance from these variable. The findings of Study Five further the collective understanding of the broader factors constituting race performances and highlights the importance of rowing technique in overall performance.

Chapter Six builds on Chapter Five by delving into the specific technical determinants of rowing performance, revealing areas of rowing technique where improvements in performance can be made. Chapter Seven is the final research chapter in this thesis and follows on from Chapters Five and Six by establishing relationships between the shape of the boat acceleration profile and rowing performance. Together with those from Chapters Five and Six, the findings from Chapter Seven reveal measures that explain overall rowing performance, therefore advancing the literature with regard to both the demands of rowing performance and the areas where improvements in performance can be attained.

Chapter Eight is the final chapter in this thesis and incorporates an overall discussion and conclusion of the research conducted and its outcomes. The findings of the research chapters are evaluated with respect to their impact across a broader research domain, as well as their practical applications in the rowing community and their potential extension to other sports. All citations in this work are presented in American Psychological Association (APA) 6th edition referencing and are collated after Chapter Eight. Appendices constitute the remaining sections of this thesis, and include research agreements, study information sheets for participants, study research flyers, study consent form templates, research ethics approval letters, and statistical analysis software (SAS) scripts for statistical analyses.

1.4 Significance of the Thesis

Rowing race performance will be improved by understanding of the relative contributions of factors to performance, and a valid system for their measurement. Knowledge of the error and limitations of measurement systems will inform the repeated assessment of performance related factors and the evaluation of their progression, while insight to the relative contributions of factors to performance will enable effective and targeted training objectives. Therefore, this thesis seeks to contribute to the literature by establishing the validity and device reliability of commercially available rowing instrumentation systems for the measurement of oar angles and power. Establishment of the magnitudes of systematic bias in devices, between-unit differences in systematic bias, and their random error magnitudes will inform the interpretation of oar angle and power measures. Secondly, this thesis will further the currently limited understanding regarding the prediction of on-water rowing race performance, and the contribution of measures of rowing technique to rowing performance. From a practical perspective, this knowledge will enable coaches and sport scientists to identify specific areas where performance improvements can be attained in the athletes they work with.

Chapter Two: Literature Review of current and prospective measures for rowing performance assessment

2.1 Introduction

Performance assessment provides insight into athlete responses to training, ensuring the prescribed stimulus is appropriate and effective in achieving the desired adaptive and performance outcomes. However, rowing performance assessment can be troublesome due to the need for precision, considering the ~ 1% variation in elite rowing performance time over 2000 m within a year, corresponding to a smallest worthwhile change estimate of ~ 0.3% for rowing performance time and ~ 1% for power output (T. B. Smith & Hopkins, 2011). Performance measures should also consider the technical demand of rowing, given rowing technique is estimated to explain ~6% of energy losses in the rower-boat system (Hofmijster, Van Soest, & De Koning, 2009; Kleshnev, 2007). Therefore, rowing performance measures need to be carefully examined for their comprehensive ability to detect small meaningful changes in both physiological and technical aspects of rowing performance.

Boat velocity and ergometer performance are the two predominant performance assessment measures in rowing, but limitations exist with both measures. Although Global navigation satellite systems (GNSS) have adequate precision for the assessment of rowing race performance (T. B. Smith, 2011), reliability issues associated with assessing boat velocity arise due to the variability of environmental conditions and their influence on boat speed. Differences in environmental conditions have been estimated to account for variations of ~ 3% in race times in international regattas (T. B. Smith & Hopkins, 2011), with variations in wind direction estimated to contribute to differences in boat velocity of up to 25% in small boat classes (Filter, 2009; Kleshnev, 2009). Performance assessment on the rowing ergometer has adequate reliability (Soper & Hume, 2004a) and enables physiological assessment in a controlled environment. However, key performance, physiological and kinematic differences exist between ergometer and on-water rowing, questioning rowing ergometer measures as a valid reflection of on-water rowing performance.

Rowing is a sport with high technical demand, whereby a rower's on-water performance is a product not only of their physiological work capacity but their ability to transfer this work to the water whilst minimising resistive drag forces to efficiently maximise forward propulsion of the boat. Assessment of technical proficiency is therefore another key rowing performance measure that requires consideration. Rowing instrumentation systems have been used to assess technique, allowing for the quantification of on-water stroke power, force, catch and finish angles, catch and finish slips, and boat acceleration characteristics (see section 2.3.3 and Figure 2.3 for descriptions of these variables), therefore providing a comprehensive assessment of rowing performance. However, little research examining the relationship between these variables and rowing performance has been undertaken and knowledge regarding the influence of technique on rowing performance is largely theoretical. Furthermore, the validity of power output and rowing-specific oar angle analysis has not been established in commercially available instrumentation systems, limiting the use of these devices as on-water rowing performance assessment tools. Nevertheless, instrumentation systems present a comprehensive measure of on-water specific rowing performance that may prove more reliable than measures of boat velocity.

2.1.1 Purpose of the review

The purpose of this review is to discuss current measurement practices for the assessment rowing performance, highlighting the need for a precise, reliable and comprehensive measure of both physiological and technical aspects of performance. Specifically, this review will evaluate the measurement of boat velocity, ergometer performance, and methods of technical analysis before discussing the use of rowing instrumentation systems in cycling and their prospective use in rowing.

2.2 Overview of rowing performance and training practices

Rowing presents a unique sport whereby races are held over 2000 m in different boat classes comprising of sweep (one oar per rower) and sculling (two oars per rower), lightweight (≤ 59 kg female, ≤ 72.5 kg male) and heavyweight events (no body mass restrictions) with crew numbers ranging from one rower in a single scull up to eight rowers and a coxswain in an eight. Twenty boat classes exist in international racing; however, this is restricted to 14 at Olympic Games regattas, which promote equal boat classes between male and female events and include two lightweight classes. World's best times are recorded as the fastest time to complete 2000 m in international regattas for each boat class and range from 5:18.68 for a Men's eight to 7:24.46 for a lightweight Women's single scull, with times typically recorded on "fast courses" where advantageous tail wind and stream flow conditions contribute to fast race times.

Typical race pacing strategies employ a reverse J-shape (Figure 2.1) where the fastest 500 m of the race is rowed at the start, followed by a slower middle 1000 m and end-spurt making the final 500 m the second fastest. The magnitude of deviation from mean boat velocity depends on the gender and boat class (Figure 2.1) with small boats (single sculls, coxless pairs and double sculls) demonstrating greater deviations compared to larger boat classes (fours, quadruple sculls and eights) where a more evenly paced strategy is employed (Chu, Sheehan, Davis, & Chang-Tsai, 2018; Kleshnev, 2000). The reverse-J shape strategy has been utilised by successful crews in recent years, with winning crews at the 2016 Olympic Games demonstrating mean velocity deviations of +3.6%, -1.7%, -2.4%, +0.5% per 500 m (Kleshnev, 2016). Larger variations in boat velocity were evident in winning crews (4.1%), compared to second (3.7%) and third (3.8%) placings at the 2016 Olympic Games (Kleshnev, 2016). No significant difference in mean boat velocity deviations between 1st-3rd and 4th-6th placings were observed at the 2000 Olympic Games, 2001 and 2002 World Championship regattas (Garland, 2005), indicating a pacing shift by successful crews away from more evenly paced strategies in recent years. The reverse J-shaped pacing strategy allows rowers the psychological advantage of being in front where they can see their field of competitors and therefore control the race tactically. However, a more even pacing strategy is physiologically advantageous given the metabolic cost of rowing is estimated as boat velocity multiplied by a coefficient of 2.4, whereby greater variations in velocity require greater energy expenditure for the same given mean boat velocity (Secher, 1993).

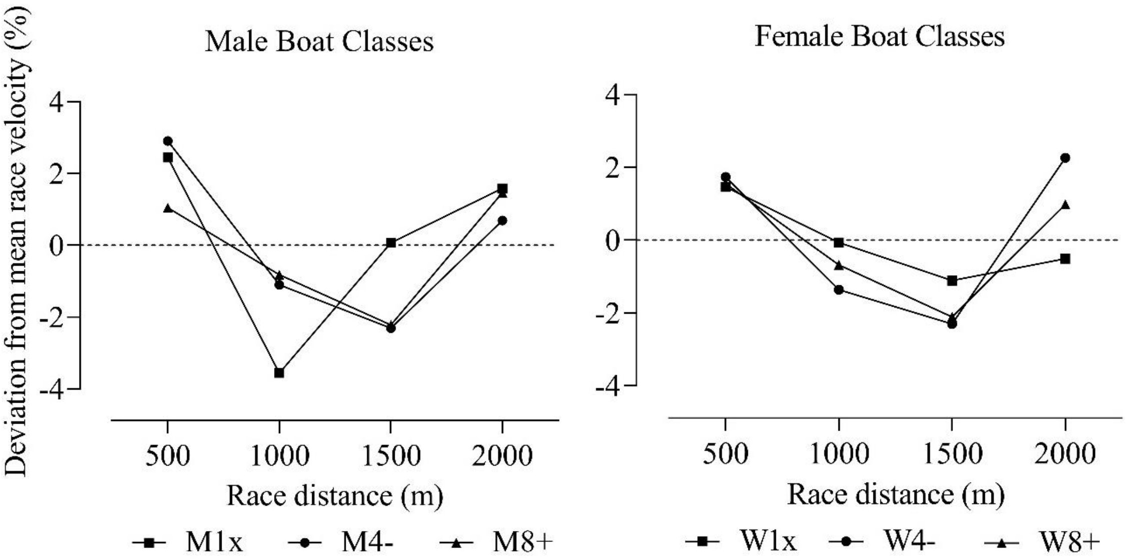

Figure 2.1 Percentage deviation from mean race velocity for male (left) and female (right) crews racing in A Finals at the 2019 Rowing World Championships. Data are means of A finalists in each boat class. M1x, men's singles; M4-, men's coxless fours; M8+, men's eights; W1x, women's singles; W4-, women's coxless fours; W8+, women's eights.

Rowing can be classified as an intermediate duration sport whereby large demands are placed on both the rower's aerobic and anaerobic energy systems throughout a race. Mean contributions of 87% aerobic and 13% anaerobic energy sources to a 2000 m on-water rowing time trial in a single scull have been reported (de Campos Mello, de Moraes Bertuzzi, Grangeiro, & Franchini, 2009). However, energetic contribution can vary between rowers for the same given performance. Highly trained rowers have differences of up to 8% in aerobic contribution to a 6 min maximal rowing ergometer test while achieving the same performance result (mean test power within 1%) (Holt, Plews, Oberlin-Brown, Merien, & Kilding, 2018), illustrating the non-uniformity of rower energetic profiles.

Typical training characteristics of elite rowers include 12-24 $h \cdot wk^{-1}$ (Fiskerstrand & Seiler, 2004; Guellich, Seiler, & Emrich, 2009; Mikulić & Bralic, 2017; Plews, 2011; Plews & Laursen, 2017; Plews, Laursen, Kilding, & Buchheit, 2014; Tran, Rice, Main, & Gastin, 2015) and rowing distances of 120-140 $km \cdot wk^{-1}$ (Lacour, Messonnier, & Bourdin, 2009; Plews, 2011; Tran et al., 2015). Training intensity distribution follows a polarised model where 67-95% of training is performed at low intensities (< 2 $mMol \cdot L^{-1}$ blood lactate [BLa]; < the first lactate threshold [LT_1]), 15-30% at moderate intensities

(2-4 mMol·L $^{-1}$ BLa; LT_1- the second lactate threshold [LT_2]), and 2-6% at high intensities (> LT_2) in elite rowers (Fiskerstrand & Seiler, 2004; Hartmann, Mader, & Hollmann, 1990; Lacour et al., 2009; Mikulić & Bralic, 2017; Plews, 2011; Plews & Laursen, 2017; Plews et al., 2014; Tran et al., 2015). These training characteristics contribute to the large aerobic capacities observed in elite rowers, as depicted by the physiological characteristics of elite rowers presented in Table 2.1.

Table 2.1 Physiological characteristics of elite rowers (range or mean ± SD)

Category	$\dot{V}O_{2max}$ (L·min^{-1})	MAP (W)	LT_1 Power (W)	LT_2 Power (W)	Reference
Heavyweight male	5.89 – 6.99	413 – 552	187 – 330	284 – 410	Fiskerstrand and Seiler (2004); Godfrey, Ingham, Pedlar, and Whyte (2005); Ingham, Carter, Whyte, and Doust (2007); Lacour et al. (2009); Mikulic and Bralic (2017); Plews and Laursen (2017); Tanner and Gore (2013); Vogler, Rice, and Gore (2010); Vogler, Rice, and Withers, (2007)
Heavyweight female	4.17 – 4.19	287 – 305	172.4 ± 21.8	238.2 ± 17.9	Tanner and Gore (2013); Vogler, Rice and Withers (2007)
Lightweight male	5.12 ± 0.3	412.5 ± 25.2	231.3 ± 24.9	312.0 ± 20.1	Tanner and Gore (2013)
Lightweight female	3.61 ± 0.2	273.9 ± 29.4	167.7 ± 24.3	217.9 ± 23.2	Tanner and Gore (2013)

$\dot{V}O_{2max}$ (maximal oxygen uptake); MAP (maximal aerobic power); LT_1 (first lactate threshold); LT_2 (second lactate threshold).

2.3 Current measurement practices of rowing performance

2.3.1 Measures of boat velocity

Measures of boat velocity are commonly used to assess on-water rowing performance as 2000-m race time is the ultimate measure of success in international racing. Impeller units, GNSS, and stopwatch timing can be used to measure boat velocity; however, comparison of performances using these measures can be problematic due to the influence of varied environmental conditions.

2.3.1.1 Global navigation satellite system (GNSS) derived velocity

Global navigation satellite system (GNSS) technology is a commonly used tool in the assessment of boat velocity in rowing. Receiver units require signals from at least four satellites, from which distance and velocity are derived using the Doppler-shift method where displacement is calculated from changes in satellite signal frequency (Schutz & Herren, 2000). Greater positional precision is achieved where more satellites are available to the receiver (Witte & Wilson, 2004). Positional precision is also influenced by horizontal dilution, whereby close proximity between satellites reduces precision (Witte & Wilson, 2004). Limitations in GNSS precision also occur due to satellite signal obstruction from surrounding objects such as buildings and the reflective surface of water (Zhang et al., 2004).

The use of GNSS is common in rowing where GNSS receiver units (placed on the boat's bow or stern canvas) allow for performance monitoring via distance and boat velocity analysis. However, the majority of research investigating GNSS as performance monitoring tools has been conducted in team sports where GNSS-derived distance and velocity data provides insight to game demands and the quantification of external training loads (Scott, Lockie, Knight, Clark, & Jonge, 2013). Therefore, relating findings regarding the validity of devices to rowing proves difficult. The linear nature of 2000 m rowing racing and higher movement velocities achieved (4-6 $m \cdot s^{-1}$) do not reflect the measurement demands of research undertaken in team sports. Furthermore, rowing poses a unique challenge for GNSS based velocity analysis, whereby intra-stroke boat velocity varies by approximately 2 $m \cdot s^{-1}$ (Hau & Guo, 2003; Hill & Fahrig, 2009; Kleshnev, 2002) from an average boat velocity of 5-6 $m \cdot s^{-1}$. Accelerometers with sampling rates of 100 Hz in GNSS receivers provide greater sensitivity to oscillations in velocity, improving GNSS accuracy via implementing algorithms utilising the accelerometer data (Coutts & Duffield, 2010). However, GNSS based accelerometers under-reported intra-stroke boat velocity by 0.14-0.19 $m \cdot s^{-1}$ in elite flatwater kayakers, compared to high-speed (100 Hz) video analysis (Janssen & Sachlikidis, 2010), demonstrating GNSS-based accelerometer units lack the accuracy required to assess intra-stroke boat velocity variation.

When examining the validity of GNSS for linear distance and velocity measures, a range of error rates have been reported. No clear difference has been identified between GNSS with 5, 10, and 15 Hz sampling rates in the accuracy of distance measurement (Vickery et al., 2014); however, higher error rates for distance measurement have been reported with linear movement (2.6-23.4% standard error of the estimate; % SEE) than that for frequent changes of direction (0.4-12.7% SEE) (Jennings, Cormack, Coutts, Boyd, & Aughey, 2010; Petersen, Pyne, Portus, & Dawson, 2009; Portas, Harley, Barnes, & Rush, 2010). Precision in GNSS velocity measurement during linear movement is compromised at 5 Hz, with errors of 3.6-11.1% CV (Varley, Fairweather, & Aughey, 2012; Waldron, Worsfold, Twist, & Lamb, 2011); however, this error decreases at 10 Hz (3.8-8.3% CV [Varley et al., 2012]), with no further reductions in error evident at 15 Hz (Johnston et al., 2012; Vickery et al., 2014).

Differences between GNSS in sampling rate, chip sets, and filtering methods are suggested to contribute to the unsystematic error rates reported for inter-unit reliability of distance (0.7-12.4% CV) and velocity (2.0-5.3% CV) measurement during linear running (Castellano, Casamichana, Calleja-González, San Román, & Ostojic, 2011; Gray, Jenkins, Andrews, Taaffe, & Glover, 2010; Varley et al., 2012). Intra-unit reliability of distance measurement is also poor (1.85-77.2% CV) (Castellano et al., 2011; Coutts & Duffield, 2010; Gray et al., 2010; Jennings et al., 2010; Petersen et al., 2009; Portas et al., 2010). Consequently, it is recommended that devices are not used interchangeably for long-term performance monitoring (Jennings et al., 2010). The CV reported in many of these studies falls outside the 0.3% smallest worthwhile change for rowing performance (T. B. Smith & Hopkins, 2011). Nevertheless, the error reported for distance measurement via 1 Hz GNSS devices in elite rowers over 22 international races is trivial (0.2% SEE) (T. B. Smith, 2011), demonstrating their effective application in the assessment of race performances in rowing where environmental conditions are consistent.

2.3.1.2 Impeller derived boat velocity

Electromagnetic impellers located on the boat's hull are used in rowing to measure distance travelled and boat velocity. The flow of water over the boat's hull acts to rotate the impeller with rotations detected by a sensor located inside the boat allowing the calculation of boat velocity and distance. Given the flow of water past the boat's hull directly influences the impeller's rotational velocity, the measurement of boat velocity is not influenced by stream conditions. Impeller derived measures of boat velocity have the sensitivity to characterise intra-stroke boat velocity fluctuations from changes in the flow rate of water detected within a stroke, providing valuable insight into rowing technique. Their assessment of boat velocity relative to the water provides a more valid measure of rowing performance in varying tide and current conditions than GNSS derived boat velocity where boat velocity is measured relative to land without consideration of stream conditions. However, impeller derived boat velocity and distance variables do not account for the influence of wind and water temperature, resulting in invalid measures of rowing performance where these environmental conditions vary (Kleshnev, 2009).

Placement of the impeller unit on the boat's hull must be carefully considered to avoid issues regarding the flow of water in the boat's boundary layer. The boundary layer consists of two types of water flow across the hull: laminar and turbulent flow. Laminar flow occurs at the bow and, depending on boat velocity and hull shape, extends approximately four metres towards the boat's stern (Nielsen Kellermen, Boothwyn, PA, USA, unpublished findings). Boat resistive drag is smallest in areas of laminar flow where the water moving past the boat does so linearly; therefore, although placement of the impeller in this area results in an even flow of water across the impeller allowing a more accurate reflection of water flow relative to the boat, it is not usually recommended by manufacturers given the impeller's shape and size disrupts the laminar flow resulting in increased resistive drag. Turbulent flow occurs following the area of laminar flow and increases in thickness towards the boat's stern where water flow is no longer linear, increasing the boat's resistive drag (Pulman, 2005). Impeller placement is recommended five metres back from the bow to ensure placement in the turbulent flow and therefore not adding to drag forces (Nielsen Kellerman Australia, 2017). One of the few manufacturers of rowing specific impellers claim the addition of an impeller contributes approximately 0.1% of total hull drag for a single scull (Nielsen Kellermen, Boothwyn, PA, USA, unpublished findings), with drag contribution presumed to decrease proportionately with boat size, and impeller size suggested to have no further drag contribution when located within the turbulent flow. Nevertheless, inaccuracies in velocity calculation are suggested to occur with impellers located in the turbulent flow due to the influence of eddy currents disturbing water flow past the impeller. Furthermore, the boundary layer itself represents a body of water that is accelerated with the boat's hull and is therefore moving at a different velocity to the unaffected water further away from the hull (Pulman, 2005), raising further issues with impeller-derived boat velocity when the impeller is located within the boundary layer.

Frequent calibration of impeller units is necessary to avoid inaccuracies in boat velocity and distance calculation. Impeller distance and velocity calibration requires rowing a known land distance in one direction and back to the starting point. This calibration process should account for the influence of the boundary layer on boat velocity calculation; however, this relationship will be influenced by water depth and boat velocity so re-calibration where these conditions change is necessary. No peer reviewed research investigating the reliability and validity of impeller derived boat velocity and distance exists, so the accuracy of these devices is uncertain. Furthermore, race distance measurement in elite rowers over 61 international 2000 m races indicate impeller units to display a random error of 1.2%, indicating impeller units lack the precision to accurately quantify race performances (T. B. Smith, 2011). Regardless, research is required to establish the validity and reliability of impeller units as boat velocity measurement tools if they are to be implemented in elite rowing programs.

2.3.1.3 Influence of environmental conditions on boat velocity

Boat velocity measurements taken in still weather conditions provide an accurate reflection of rowing performance, however variations in environmental conditions have a considerable impact on boat velocity. Boat velocity is predicted to decrease by 1.3% with a 15 °C reduction in water temperature (Filter, 2009) due to reduced molecular mobility and increased resultant frictional resistance. Wind resistance is estimated to account for 11.5% of total drag forces acting on the boat-rower system (Kleshnev, 2009), with high velocity (> 5 $m \cdot s^{-1}$) headwinds (across the bow between parallel and 30° to the boat's long axis) having the greatest impact on boat velocity. Differences are evident between boat classes in the impact of wind on boat velocity, with a 5 $m \cdot s^{-1}$ headwind estimated to reduce boat velocity by 17.4% and 12.2% in 1x and 8+ classes respectively (Filter, 2009; Kleshnev, 2009). Similarly, 5 $m \cdot s^{-1}$ tail winds (across the stern) increase boat velocity in single sculls (7.5%) to a greater extent than in eights (5.1%), while direct crosswinds (perpendicular to the boats long axis) have a greater reduction on boat velocity in an eight (4.1%) than a single scull (1.6%) (Filter, 2009; Kleshnev, 2009). This pronounced environmental influence on small boat classes is supported by the possibly small increase in final-to-final random variation observed in the mean race time of small boats (single sculls; 1.19 ×/÷ 1.06% ES; effect size) at international regattas between 1999-2009 (T. B. Smith & Hopkins, 2011). A ~3% influence of environmental conditions on race time has been estimated from the 2.9 ×/÷ 1.13% CV venue-to-venue and 2.8 ×/÷ 1.04% CV final-to-final random variation identified in mean race time in international regattas (T. B. Smith & Hopkins, 2011). This ~3% variation in race time due to environmental conditions falls outside of the 0.3% smallest worthwhile change for rowing performance time which was established from the 1% within-boat final-to-final variation in race times (T. B. Smith & Hopkins, 2011), confirming the variability of boat velocity due to unavoidable environmental influences impairs the sensitivity of boat velocity measures in detecting true changes in rowing performance.

2.3.2 Ergometer measures of rowing performance

Due to the reliability issues associated with boat velocity measures where environmental conditions differ, and the difficulty evaluating individual performances in crew boats, ergometer testing is a common method of off-water rowing performance assessment providing a measure of physiological rowing capacity that is less affected by technical proficiency than on-water rowing. However, the validity of ergometer performance as a measure of on-water rowing performance is questionable with differences evident in performance, physiological, and kinematic variables between ergometer and on-water rowing. Nevertheless, ergometers allow physiological assessment in a controlled environment that is often unattainable on-water due environmental variation, enabling physiological characteristics (Table 2.1) and determinants of 2000 m rowing ergometer performance to be established. Although, little is known regarding the translation of these physiological determinants to on-water rowing.

2.3.2.1 Measures of performance on stationary ergometers

The Concept2 (Concept2 Inc., Morrisville, VT) stationary rowing ergometer is widely accepted as the most commonly used tool for the assessment of off-water rowing performance in the international rowing community. Concept2 air-braked ergometers incorporate a fixed flywheel and foot-plate design, which remains stationary throughout the rowing stroke. This requires the rower's centre of mass (positioned on a sliding seat) to be accelerated through an anterior-posterior direction along a slide via reactive forces occurring from the application of force at the footplate (Figure 2.2). Stationary ergometers have been criticised for biomechanical differences to on-water rowing, given no fixed point of force transfer exists (Elliott, Lyttle, & Birkett, 2002) and the acceleration of the rower's centre of mass occurs relative to the acceleration of the boat-rower system on-water (Kleshnev, 2002).

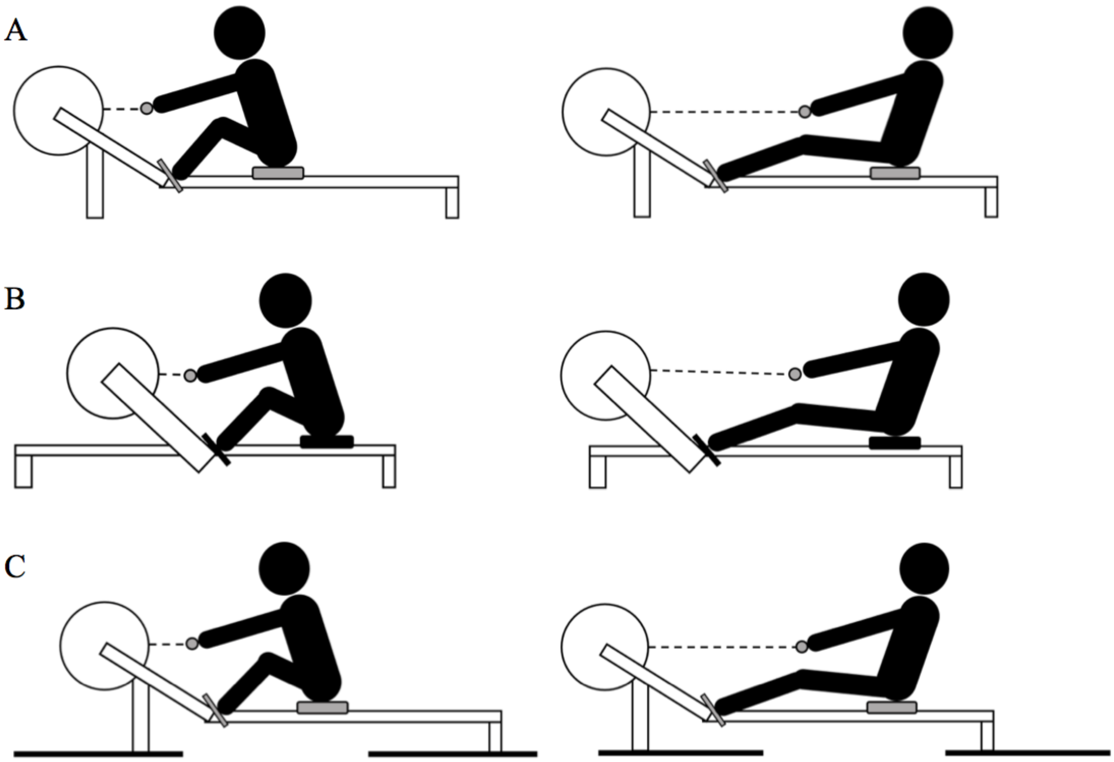

Figure 2.2 Representation of stationary (A) and dynamic (B) ergometers, and stationary ergometer on slides (C).

The validity of power measurement from Concept2 ergometer models A and D has been investigated using mechanical sensors attached to the ergometer, with negative bias estimates of 5-8 % found for the Concept2 (Boyas, Nordez, Cornu, & Guével, 2006; Lormes, Buckwitz, Rehbein, & Steinacker, 1993), whereby greater negative bias appeared to be associated with larger stroke-to-stroke variations in power output performed by the rower (Boyas et al., 2006). The Concept2 ergometer has proven to be reliable over time trial distances of 2000 m (Schabort, Hawley, Hopkins, & Blum, 1999; Soper & Hume, 2004a) and 500 m (Soper & Hume, 2004a), and of 90 s duration (Macfarlane, Edmond, & Walmsley, 1997a). The investigation of repeated 2000 m Concept2 performance in 15 national level rowers revealed small changes in mean test power (1.3% SEM; standard error of the measurement) and duration (0.7% SEM), with very high retest correlations for both mean power (0.99 ICC; intra-class correlation coefficient) and duration (0.99 ICC) (Soper & Hume, 2004a). Comparably high retest correlations for 2000 m performance are also evident in school-level rowers for mean test power (0.96 ICC) and duration (0.97 ICC), with corresponding CV of 2% and 0.6% for mean power and test duration respectively (Schabort et al., 1999). Reliability decreases with test duration, with more variance in mean power (2.8% SEM) and duration (1.0% SEM) evident over 500 m, likely reflective of a less consistent pacing strategy and higher mean velocity performed (Hopkins, Schabort, & Hawley, 2001; Soper & Hume, 2004a). The reliability of performance has also been assessed through the instrumentation of a Concept2 ergometer, allowing analysis of peak power, mean power, work performed, time to peak force occurrence at the handle and footplate, as well as stroke rate and distance rowed over repeated 90 s performances (Macfarlane et al., 1997a). Retest correlations proved high in all of these variables (0.79-0.96 ICC), with 3.1% CV for mean power and 2.4% CV for distance rowed (Hopkins et al., 2001; Macfarlane et al., 1997a). Overall, the measures of reliability presented for Concept2 performance fall within the range typically seen in cycling time trials (0.6-4.6% CV) (Hopkins et al., 2001), with 2000 m test duration reliability falling within the 1% SEM for on-water rowing performance (T. B. Smith & Hopkins, 2011). The reliability of Concept2 is therefore considered to be adequate for repeated performance assessments (T. B. Smith & Hopkins, 2012).

Performance differences between stationary ergometer and on-water rowing exist in completion time, velocity, distance rowed, power, stroke rate, pacing strategy, and ranking. Performance time is substantially quicker on stationary ergometers than over an equivalent distance performed on-water in a single scull (Table 2.2), demonstrating stationary ergometers more closely simulate faster boat classes (Bazzucchi et al., 2013; de Campos Mello et al., 2009). Wind and stream flow are factors contributing to resistive drag that do not effect ergometer performance (Kleshnev, 2009); however, ergometer calculation of distance covered is expected to be the main contributor to the discordance in performance time. Furthermore, the identification of a large relationship (r = 0.68) between body mass and ergometer performance, but not single scull performance (r = 0.04) has led to the development of a "power-to-weight" ratio for the prediction of single scull velocity from ergometer velocity (ergometer velocity x body mass$^{-0.23}$) in an effort to improve the ergometer's predictive ability of on-water performance (Nevill, Beech, Holder, & Wyon, 2010). Additionally, more even pacing strategies employed in ergometer performances than those on-water have been observed, corresponding to a slower paced first 500 m and faster middle 1000 m on the ergometer (Garland, 2005).

Table 2.2 Stationary ergometer and on-water differences in performance, physiological, and kinematic variables. Mean difference denoted in brackets

Authors	Participant Characteristics	Performance Measure	Outcome (ergometer vs. on-water)
Performance Variables			
Bazzucchi et al. (2013)	9; Elite (5), Highly Trained (4)	1000 m TT	↓ TT time (23%)
Nevill, Beech, Holder, and Wyon (2010)	49 M; Highly Trained	2000 m TT	↑ TT velocity (36%)
Vogler, Rice, and Gore (2010)	7 M; Highly Trained	6 x 4 min (160 W start; ↑ 35 W), 1 x 4 min max	↑ Distance (19%) ←→ W @ LT_1 & LT_2 ↑ W (8%), distance (22%)
de Campos Mello, de Moraes Bertuzzi, Grangeiro, and Franchini (2009)	8 M; Trained	2000 m TT	↓ TT time (44%)
Physiological Variables			
Bazzucchi et al. (2013)	9; Elite (5), Highly Trained (4)	1000 m TT	↑ HR ←→ $\dot{V}_E$, $\dot{V}O_2$
Vogler, Rice, and Gore (2010)	7 M; Highly Trained	6 x 4 min (160 W start; ↑ 35 W) 1 x 4 min max	←→ HR, $\dot{V}O_2$ ↓ BLa @ LT_1 (23%) ←→ HR, $\dot{V}O_2$ @ LT_1 ←→ BLa, HR, $\dot{V}O_2$ @ LT_2 ↑ SR (8%), HR (2%), BLa (2%) ←→ $\dot{V}O_2$
de Campos Mello, de Moraes Bertuzzi, Grangeiro, and Franchini (2009)	8 M; Trained	2000 m TT	←→ Mean $\dot{V}O_2$, $\dot{V}O_{2peak}$, mean HR, HR_{max} ↓ Total energy expenditure (26%)

			↓ Aerobic energy contribution (3%) ←→ Alactic energy contribution ←→ Lactic energy contribution
Faina, De Angelis, and Aguillar (1998)	6; Highly Trained	1250 m TT	←→ $\dot{V}O_{2peak}$, mean HR ←→ $\dot{V}O_2$ amplitude, $\dot{V}O_2$ kinetics ↑ BLa (57.5%) ↓ Pre-TT $\dot{V}O_2$
Kinematic Variables			
Murbach, York, Howard, Klaudt, and Higginson (2018)	9 M; Trained	3 x 2 min @ 20 strokes·min^{-1}	↑ GS EMG (33%) ↑ BF EMG (45%) ↑ VL EMG (56%) ↑ RF EMG (50%) ↓ Time to peak RF activation
Fleming, Donne, and Mahony (2014)	10 M; Highly Trained	3 x 3 min @ 75, 85, 95% $\dot{V}O_{2peak}$	↓EMG VM (6%) (drive phase) ↓EMG ES (3%) (early drive phase) ←→ EMG BF
Bazzucchi et al. (2013)	9; Elite (5), Highly Trained (4)	1000 m TT	↑ EMG LD & TRS ↓ EMG RF ←→ EMG BB, VM, VL
Wilson, Gissane, Gormley, and Simms (2013)	19 M; Elite	6 x 4 min (160 W start; ↑ 40 W), 1 x 4 min max	↑ Lumbar flexion range (3.4°) ↑ Lumbar flexion max angle change (3.1°)
Baca, Kornfeind, and Heller (2006)	4 M; Elite	5 consecutive strokes	↓ Drive phase duration (11%)
Kleshnev (2005)	5 F; Trained	2 x 90 s	↑ Peak handle force (28%) ↑ Mean handle force (26%) ↑ Leg drive length (1%)

			↓ Handle velocity (9%) Later peak force occurrence (6%)
Lamb (1989)	30 M; Highly Trained	Rowing 30 strokes·min^{-1}	←→ leg and trunk kinematics Upper and lower arm movement differs to OW at the catch and finish

↓ (decreased); ↑ (increased); ←→ (no difference); M (male); F (female); $\dot{V}O_{2peak}$ (peak oxygen consumption); EMG (electromyography); TT (time trial); OW (on-water); W (watts); $\dot{V}_E$ (ventilation); $\dot{V}O_2$ (oxygen consumption); SR (stroke rate); HR (heart rate); HR_{max} (maximal heart rate); BLa (blood lactate); LT_1 (first lactate threshold); LT_2 (second lactate threshold); GS (gastrocnemius); VM (vastus medialis); ES (erector spinae); BF (biceps femoris); LD (latissimus dorsi); TRS (trapezius superior); RF (rectus femoris); BB (biceps brachii); VL (vastus lateralis); strokes·min^{-1} (strokes per minute).

On-water and ergometer performance times are more closely related in small boat classes than larger. Analysis of 2000 m ergometer time and final rankings at Junior and Elite World Championship regattas has revealed large and very large correlations (r = 0.55-0.92) for smaller boat classes (single sculls, double sculls, and coxless pairs), but moderate and small correlations (r = 0.21-0.50) for larger boat classes (eights and quads) (Mikulić, Smoljanovic, Bojanic, Hannafin, & Matković, 2009; Mikulić, Smoljanovic, Bojanic, Hannafin, & Pedisic, 2009). Technical differences between crew members within a boat in their oar placement and removal timing, force application, and movement coordination may explain the smaller correlations observed in bigger boat classes, highlighting the greater importance of technical proficiency to on-water rowing performance than that on an ergometer. As such, the differences in stationary ergometer and on-water performance presented in Table 2.2 indicate different performance demands between the two conditions. Particularly in performance time where faster times correspond to 3% smaller aerobic energy system contributions than observed on-water (de Campos Mello et al., 2009), whereby the viability of 2000 m ergometer testing as an assessment tool for on-water rowing performance is questionable.

Differences in physiological responses between stationary ergometer and on-water rowing appear less apparent than those for performance differences (Table 2.2). Higher heart rates are apparent on the ergometer during maximal but not sub-maximal performances (Bazzucchi et al., 2013; Vogler et al., 2010). Similarly, maximal and submaximal exercise elicit higher blood lactate responses on the ergometer (Faina et al., 1998; Vogler et al., 2010), while differences in $\dot{V}O_2$ between the two modalities have not been identified (Bazzucchi et al., 2013; de Campos Mello et al., 2009; Faina et al., 1998; Vogler et al., 2010). Conversely, relationships between maximal aerobic power, 30 s modified Wingate mean power, and lower limb strength are reduced when assessed relative to on-water 2000 m velocity in comparison to ergometer 2000 m velocity (Otter-Kaufmann, Hilfiker, Ziltener, & Allet, 2019).

Kinematic differences (Table 2.2) reveal handle forces to be greater and occur later in the stroke on the ergometer, with handle force curves exhibiting a triangular shape compared to the more advantageous rectangular shape produced on-water. Furthermore, the greater lumbar flexion observed on the ergometer is suggested to increase the risk of lower back injury in rowers (Millar, Reid, & McDonnell, 2018; Wilson et al., 2013).

While the altered muscle activation patterns as measured via electromyography (EMG) reflect the relative stability and greater inertial forces (related to the differing rower centre of mass acceleration profile) experienced on a stationary ergometer compared to that in on-water rowing (Bazzucchi et al., 2013; Fleming et al., 2014; Lamb, 1989; Murbach et al., 2018; Zbořilová, Sedlák, & Kračmar, 2017).

2.3.2.2 Measures of performance on dynamic ergometers

Dynamic ergometers exist in different forms and are designed to more closely replicate the feel of on-water rowing than stationary ergometers through reducing movement of the rower's centre of mass and therefore inertial forces and the resultant kinetic energy required to accelerate the flywheel, in comparison to that required to accelerate the rower's centre of mass on a stationary ergometer (Dudhia, 2017). The RowPerfect ergometer (RP3 RowPerfect, Hertogenbosch) is regarded as the most popular dynamic rowing ergometer commercially available and has been used exclusively in studies investigating dynamic rowing ergometers, as presented in Table 2.3. The RowPerfect incorporates both freely moving flywheel (with attached footplate) and seat in the anterior-posterior direction along a rail (Figure 2.2). A dynamic ergometer has also been designed by Concept2 (Concept2 Inc., Morrisville, VT) which incorporates a semi-freely moving seat (attached to a bungee cord preventing the seat moving past a certain range) and freely moving footplate, with the stationary flywheel attached to the base of the ergometer. However, research comparing this ergometer design to on-water rowing is yet to be conducted. Alternatively, slides are available for which a stationary Concept2 machine can be mounted, enabling movement of the footplate-flywheel complex (Figure 2.2). Research to date investigating the use of slides has found no difference in drive power, force curve area, knee moment forces and angular velocity, drive and recovery trunk acceleration, total mechanical energy production and joint mechanical efficiency between slides and dynamic RowPerfect ergometers (Greene, Sinclair, Dickson, Colloud, & Smith, 2013).

The reliability of dynamic ergometers has been investigated in just one study, finding good reliability for mean power over 500 m (3.0% SEM) and 2000 m (3.3% SEM) performances (Soper & Hume, 2004a). Small changes in mean time were also revealed for 500 m (1.6% SEM) and 2000 m (0.5% SEM), with high retest correlations for mean power and time over both distances (> 0.88 ICC) (Soper & Hume, 2004a). However, reliability of mean power and time was lower on the dynamic than the stationary ergometer, likely due to the lower stability of the RowPerfect (Soper & Hume, 2004a). Furthermore, 2000 m mean power produced a 2.2-7.0% SEM (Soper & Hume, 2004a), signifying changes in mean power of up to 7% may be attributable to normal variability – a substantial value when considering the smallest worthwhile change for on-water rowing power is 1% (T. B. Smith & Hopkins, 2011).

Only four studies have investigated differences between dynamic ergometers and on-water rowing performance (Table 2.3). These studies have found handle force is greater and occurs later in the drive on the dynamic ergometer, corresponding to a reduced rate of force development and impulse associated with dynamic ergometer rowing in comparison to on-water rowing (Table 2.3) (Coker, 2010; Kleshnev, 2005). Elliott et al. (2002) observed similarities in force curves between on-water and dynamic ergometer conditions with correlations coefficients of 0.91-0.93 between the two, suggesting the dynamic ergometer replicates on-water rowing movement patterns. This is disputed by differences observed in muscle activation patterns during the drive phase (Fleming et al., 2014; Murbach et al., 2018). Nevertheless, differences from on-water rowing in muscle activation patterns are smaller on dynamic in comparison to stationary ergometers, suggesting dynamic ergometers more closely replicate on-water rowing (Murbach et al., 2018).

Table 2.3 Dynamic ergometer and on-water differences. Mean difference denoted in brackets.

Authors	Participant Characteristics	Performance Measure	Outcome (ergometer vs. on-water)
Murbach, York, Howard, Klaudt, and Higginson (2018)	9 M; Trained	3 x 2 min @ 20 strokes·min^{-1}	↑ VL EMG (33%) ⟷ GS, BF, RF EMG ⟷ Time to peak RF activation
Fleming, Donne, and Mahony (2014)	10 M; Highly Trained	3 x 3 min @ 75, 85, 95% $\dot{V}O_{2peak}$	↓ drive phase time (13%) ↓ drive:recovery ratio (6%) ↑EMG VM (drive phase) (10%) ↑EMG ES (early drive phase) (10%) ⟷ EMG BF
Kleshnev (2005)	5 F; Trained	2 x 90 s	↑ peak handle force (30%) ↑ mean handle force (23%) later peak force achieved (6%) ↑ handle velocity (2%) ↑ acceleration during drive (9%) ↑ acceleration during recovery (40%)
Elliott, Lyttle, and Birkett (2002)	4 M, 4 F; Highly Trained	3 x 500m @ 24, 26, 28 strokes·min^{-1}	↑ catch knee angle @ 24 strokes·min^{-1} (3%) ⟷ force curve consistency

↓ (decreased); ↑ (increased); ⟷ (no difference); M (male); F (female); strokes·min^{-1} (strokes per minute); $\dot{V}O_{2peak}$ (peak oxygen consumption); GS (gastrocnemius); BF (biceps femoris); RF (rectus femoris); VM (vastus medialis); ES (erector spinae).

2.3.2.3 Determinants of 2000 m ergometer performance

As rowing ergometers enable physiological assessment in a controlled environment with limited technical demand compared to on-water rowing, several studies have investigated the physiological determinates of 2000 m stationary ergometer performance (Akça, 2014; Bourdin, Lacour, Imbert, & Messonnier, 2017; Bourdin, Messonnier, Hager, & Lacour, 2004; Cosgrove, Wilson, Watt, & Grant, 1999; Fumoto, Sera, Azuma, Sato, & Matsumoto, 2020; Ingham, Whyte, Jones, & Nevill, 2002; Kendall, Smith, Fukuda, Dwyer, & Stout, 2011; Kennedy & Bell, 2000; Otter-Kaufmann et al., 2019; Riechman et al., 2002; Russell, Le Rossignol, & Sparrow, 1998; Shimoda, Fukunaga, Higuchi, & Kawakami, 2009; van der Zwaard et al., 2018; Yoshiga & Higuchi, 2003). These studies reported very large (r = 0.83-0.96) (Bourdin et al., 2017, 2004; Cosgrove et al., 1999; Fumoto et al., 2020; Ingham et al., 2002; Kendall et al., 2011; Kennedy & Bell, 2000; van der Zwaard et al., 2018; Yoshiga & Higuchi, 2003), and large (r = 0.50-0.61) (Riechman et al., 2002; Shimoda et al., 2009) relationships between maximal oxygen uptake ($\dot{V}O_{2max}$) in $L{\cdot}min^{-1}$ and 2000 m ergometer performance. When expressed as $mL{\cdot}kg^{-1}{\cdot}min^{-1}$ the relationship between $\dot{V}O_{2max}$ and 2000 m ergometer performance is small (r = 0.11-0.24) (Cosgrove et al., 1999; Ingham et al., 2002; Riechman et al., 2002), corresponding to the large relationship (r =0.51-0.85) identified between 2000 m performance and body mass (Akça, 2014; Bourdin et al., 2017; Ingham et al., 2002; Riechman et al., 2002; Yoshiga & Higuchi, 2003). Conversely, power at LT_2 had correlation coefficients of 0.55 (Kendall et al., 2011) and 0.88 (Ingham et al., 2002) for 2000 m time and velocity respectively. Peak power sustained over 15 seconds (Kendall et al., 2011), 1 second (van der Zwaard et al., 2018), and five strokes (Akça, 2014; Ingham et al., 2002; Riechman et al., 2002) had a very large (r = 0.76-0.95) relationship with 2000 m performance, while 30 s modified Wingate performance also demonstrated a large relationship (r = 0.80-0.87) (Akça, 2014; Otter-Kaufmann et al., 2019; Riechman et al., 2002), reflecting the demand for anaerobic power in 2000 m racing. Similarly, leg extension strength and muscle volume had a large relationship (r = 0.54-0.92) with 2000 m performance (Akça, 2014; Bourdin et al., 2017; Huang, Nesser, & Edwards, 2007; Lawton, Cronin, & McGuigan, 2013; Otter-Kaufmann et al., 2019; Shimoda et al., 2009; van der Zwaard et al., 2018). These findings demonstrate the highly aerobic and anaerobic demands of 2000 m rowing, with parameters of both aerobic ($\dot{V}O_{2max}$ [$L{\cdot}min^{-1}$] and LT_2

power) and anaerobic capacity (peak and 30 s power) proving strong determinants of ergometer time trial success.

Research investigating whether these relationships translate to determinants of on-water rowing performance is limited, however, large correlations have been established with 2000m on-water race velocity for maximal aerobic power (r = 0.63), 30 s modified Wingate mean power (r = 0.60), and lower limb strength (r = 0.54) in national level rowers (Otter-Kaufmann et al., 2019). Therefore, aerobic capacity, anaerobic capacity, and lower limb strength are areas where substantial improvements can be made in both ergometer and on-water rowing, although the magnitudes of their effects appear to be reduced when assessed on-water.

2.3.3 Biomechanical and technical measures of rowing performance

Rowing is a sport with high technical demand, whereby an athlete's on-water performance is a product not only of their physiological work capacity, but their ability to transfer this work to the water while minimising resistive drag forces in order to efficiently maximise forward propulsion of the boat. Correspondingly, the overall efficiency of rower-boat system has been estimated between 17-20% (Hofmijster et al., 2009; Kleshnev, 2007). Although physiological efficiency explains the majority (~77.2%) of these energy losses in the system, the remainder (~6%) comprises energy losses resultant of technical elements of the rowing stroke but does not appear to be related to stroke rate (Hofmijster et al., 2009; Kleshnev, 2007), warranting consideration of the impact technical proficiency has on overall rowing performance. Parameters of rowing technique investigated in the literature include catch and finish angles, total and effective arc lengths, force and acceleration profiles, as well as within-stroke boat velocity fluctuations. The following sections will discuss these parameters in further detail, including measurement practices and their relationship with rowing performance.

2.3.3.1 Catch and finish angles: measurement and influence on performance

The term "catch" refers to the most negative oar angle achieved prior to the start of the drive phase, while the "finish" refers to the maximal positive oar angle achieved prior to the start of the recovery phase (Figure 2.3), whereby an oar angle of zero degrees occurs with the oar shaft perpendicular to the long axis of the boat (Kleshnev, 2007). The total arc length of a rowing stroke is a measure of angular displacement of the blade between the catch and finish. Typically rowing instrumentation systems are used to derive these variables via oar angular displacement around the pin enabling instantaneous feedback on catch and finish angles to the rower, corresponding to the achievement of 6% greater catch angles compared to post-row visual and verbal feedback (George, 2013).

Figure 2.3 Segments of the rowing stroke. Catch (A), early drive (B), mid-drive (C), late drive (D), finish (E), early recovery (F), mid-recovery (G), late recovery (H).

A number of factors influence the catch, finish, and arc length angles that can be achieved. Maximal arc lengths occur at moderately low stroke rates (24 strokes·min^{-1}) with reductions occurring predominantly at the catch as stroke rate increases, and larger reductions observable in sweep than sculling class boats (Kleshnev, 2007). Additionally, arc lengths increase across boat classes, with larger boats achieving greater lengths due to reduced pin spans and boat roll (Coker, 2010). Conversely, arc lengths decrease with foot-stretcher height through reduced catch angles and leg drive lengths (Liu, Gao, Li, Ma, & Sun, 2020). However, catch and finish angles within a boat class have little variation in experienced rowers, (0.5 ± 0.3% CV) over a range of stroke rates (Coker, 2010; Draper & Smith, 2006; Soper, Hume, & Tonks, 2003), revealing the degree of measurement precision required when assessing oar angles.

Larger catch and finish angles are suggested to be advantageous given the influence of lift forces on mechanical efficiency. Propulsive horizontal lift forces are present at catch angles less than -50^{o} and finish angles greater than 20^{o} where the blade acts as a hydrofoil moving through the water in the direction of boat movement, with greater arc lengths maximising these lift forces (Pulman, 2005; Robert, Leroyer, Barré, Queutey, & Visonneau, 2019). Force applied to the oar handle at the catch and finish maximise lift forces and are therefore highly efficient given kinetic energy loss to the water is limited. Consequently, the occurrence of peak force in the early drive is recommended for efficient maximisation of forward boat propulsion (Coker, 2010; Pulman, 2005). Blade velocity at the catch and the finish also affect lift forces, with entry velocities matching water velocity when the blade is half submerged at the catch suggested to maximise efficiency (Kleshnev & Baker, 2007; Macrossan & Macrossan, 2006), while rapid removal of the blade at the finish is recommended to reduce drag forces (Coker, 2010; Pulman, 2005).

Limited research has assessed the performance impact of catch and finish angle, total arc length and effective length (see definition in section 2.3.3.2). However, the relationship of these variables with boat velocity has been investigated in two elite single scullers under race conditions using the Peach PowerLine rowing instrumentation system to quantify the angular variables (Coker, 2010). Significant relationships existed between 5-stroke average boat velocity and catch and finish angle, total arc length and effective length. However, the direction of these relationships depended on the sculler assessed, with conflicting results across all measures. Moderate (*r* >0.40) positive and negative relationships were found for catch and finish angles, with the direction of the relationship reversing for catch and finish angles in both rowers (Coker, 2010). That is, larger negative catch angles and larger finish angles were related to higher boat velocities in one sculler, however in the other sculler less negative catch angles and smaller finish angles corresponded with higher boat velocities (Coker, 2010). This reversal may represent differences in the rigging between rower's boats, as this was not controlled for in the study. For a given arc length, a greater catch angle will correspond to a smaller finish angle, as more work is performed with the blades near the bow. Although greater catch angles are suggested to enhance boat velocity (Coker, 2010; Kleshnev, 2007), it is possible that one of the rowers in the study benefits more from greater finish angles. However, relationships were also conflicting for arc lengths, with large (*r* >0.50) positive and negative correlations with boat velocity evident for total arc length, and moderate positive ($r = 0.44$) and large negative ($r = -0.60$) relationships observed between effective length and boat velocity (Coker, 2010).

2.3.3.2 Catch and finish slips: measurement and influence on performance

The time or angular displacement between the change of direction of the blade at the catch or finish and the angle where the blade is considered to contribute to forward propulsion of the boat is termed the catch/finish slip, as illustrated in Figure 2.4. The effective arc length is determined by accounting for the catch and finish slips, which are estimated to contribute to 4.9% of efficiency losses (Kleshnev, 2007) and should therefore be considered in technical proficiency and performance assessment.

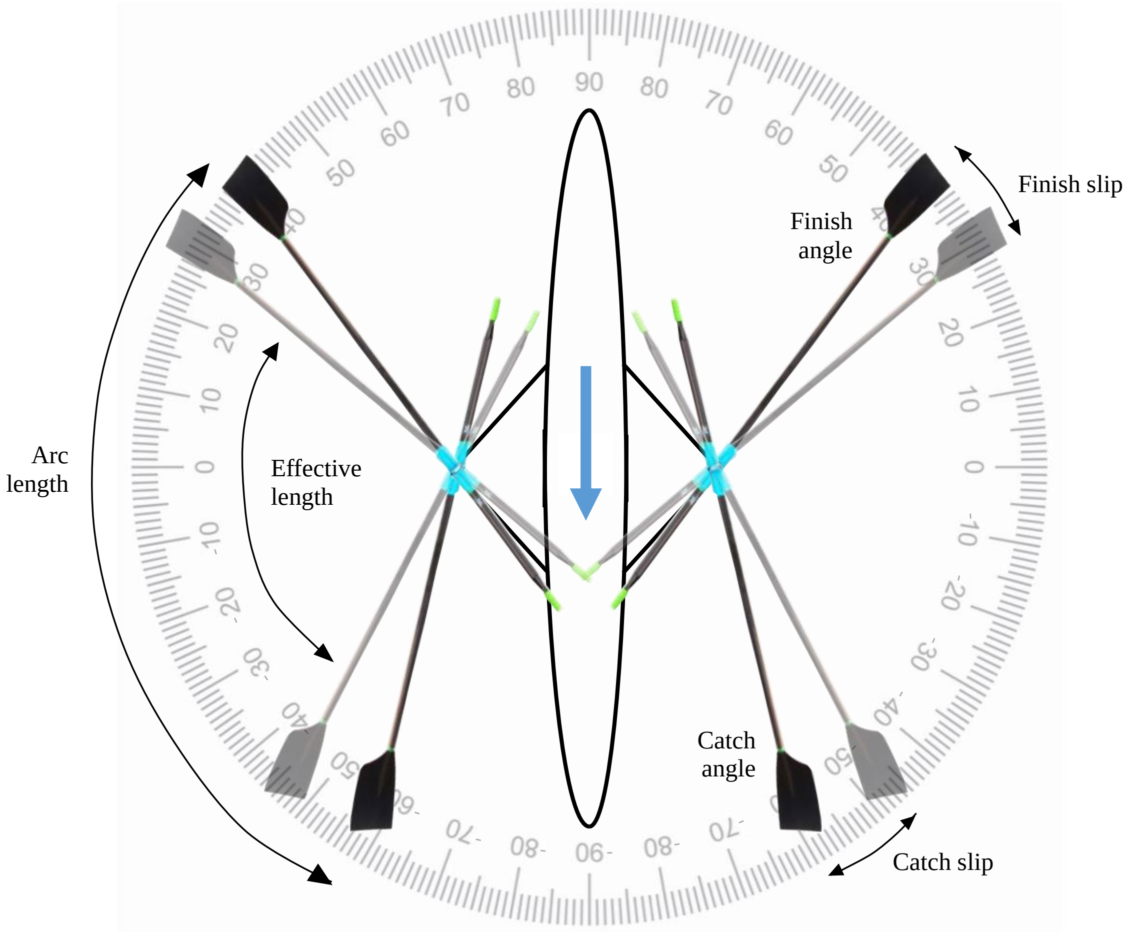

Figure 2.4 Overhead diagram of a single scull illustrating typical catch and finish angles, catch and finish slip, arc length and effective length angular displacements. The blue arrow indicates the direction of boat travel.

Various criteria for the measurement of catch slip have been proposed, these include the time taken or angular displacement between the catch and: a predetermined force threshold, the occurrence of 30% of peak stroke force (Kleshnev, 1998), positive boat acceleration (Coker, 2010), and complete or partial submersion of the blade (Kleshnev, 2007). Similarly, methods of finish slip quantification include time or angular displacement from the aforementioned variables (excluding positive boat acceleration) and finish angle (Coker, 2010; Kleshnev, 1998, 2007).

Catch and finish slips can be quantified by rowing instrumentation systems such as the Peach PowerLine and Nielsen-Kellerman EmPower systems from predetermined force thresholds, which allow instantaneous feedback to athletes, enabling the effect of technical changes to be observed. However, this method is sensitive to transverse forces and forces applied to the pin around the catch and finish to provide the oar acceleration for changes in rotational and translational velocities, however have limited translation to forward propulsion of the boat. These forces produce measurement inaccuracies in the form of reduced catch slip values that correspond to larger resistive drag forces and smaller total arc lengths (Macrossan & Macrossan, 2006). Additionally, predetermined threshold values differ between rowing instrumentation systems with the Peach PowerLine system implementing default force thresholds of 196 N and 98 N for catch and finish slips respectively (Coker, 2010), and the EmPower system 100 N for both catch and finish slips in sculling boats, contributing to differences in effective arc length measures between the two systems. To date comparison of relationships between catch slip and boat velocity over multiple methods of catch slip quantification have been investigated in just one study by Coker (2010) which examined race conditions in two elite single scullers. The relationship between catch slip calculated via the Peach PowerLine system (i.e., 196 N force threshold) and boat velocity demonstrated a substantial effect in only one of the rowers, with a large negative relationship (r = -0.60) between the two variables, indicating that increasing catch slip values measured in this way negatively influences boat velocity. No research investigating the influence of EmPower calculated catch slip or any method of finish slip quantification on boat velocity has been conducted.

Angular displacement to 30% of peak stroke force considers an athlete's capacity for force production and therefore provides an individualised measure of catch and finish slips (Coker, 2010). However, the calculation of angular displacement to 30% of peak stroke force requires analysis of rowers' force and angle data following their collection making instantaneous feedback not feasible, unless an estimated threshold value calculated from previously collected peak force values is used. As with methods implementing predetermined force thresholds, this method also faces issues regarding its sensitivity to transverse forces and those applied while the blade is out of the water. Nevertheless, an increase to the percentage of stroke force above 30% peak stroke force (i.e. reduced catch slip values) has an association with improved blade efficiency (r = 0.55) (Kleshnev, 1998). Conflicting results were found regarding the relationship between angular displacement to 30% peak stroke force and boat velocity by Coker (2010), with the two scullers demonstrating moderate positive (r =0.42) and small negative (r = -0.28) relationships respectively. Technical differences are suggested to explain these contradictory findings with the likelihood that smaller catch slip values achieved by “rowing it in” corresponded negatively with boat velocity, but further investigation incorporating a larger sample size is required regardless.

The assessment of catch slip via time taken from the catch position to positive acceleration of the boat aims to identify the enhanced ability of successful rowers to accelerate their centre of mass rapidly at the catch (discussed in further detail in section 2.3.3.2) (Coker, 2010; Kleshnev, 2010a). Initial research by Coker (2010) revealed conflicting results when assessed in two elite rowers, finding both small positive (r = 0.20) and negative (r = -0.22) relationships between time to positive boat acceleration and boat velocity. Nevertheless, highly trained rowers make better performance judgements on catch timing and the resultant boat velocity when catch slip was determined from time to positive acceleration (0.59 ± 0.42; standardised mean difference ±SD) than time to 30% peak force (0.59 ±0.42) and time to 196 N (0.59 ± 0.42) (Millar, Oldham, Hume, & Renshaw, 2015).

Angular displacement between the catch and complete submersion of the blade is proposed as another measure of catch slip (Kleshnev, 2007), however propulsive force can be generated prior to complete blade submersion (Coker, 2010). As submersion of half the blade is considered to contribute to forward propulsion this has also been recommended as a parameter for catch and finish slip measurement and corresponds to larger correlations with blade propulsive efficiency (r = 0.45) than complete blade submersion (r = 0.38) (Kleshnev, 2007). Nevertheless, research by Coker (2010) failed to identify a significant relationship between angular displacement from the catch to complete blade submersion and mean boat velocity across one stroke cycle. Furthermore, this method of catch slip quantification proves time consuming and difficult to analyse with high-speed cameras required to accurately identify the point of blade submersion.

Catch slip derived by the time taken to positive boat acceleration appears to be the most relevant measure of the four methods discussed, however still has limitations. Given peak boat acceleration has been shown to occur earlier and have a greater magnitude in more successful rowers, time taken to positive boat acceleration appears to be an important measure of rowing performance and therefore catch slip (Hill & Fahrig, 2009; Kleshnev, 2010a). Additionally, the association of this measure with rowers’ ability to identify strokes where their catch had a positive influence on boat velocity (Millar et al., 2015) demonstrates the internal feedback associated with this measure, likely allowing better self-regulation of technique and therefore rowing performance. However, the delayed calculation of catch slip via time to peak boat acceleration, as well as angular displacement to complete or partial blade submersion, and 30% of peak stroke force reduces the ability for instantaneous feedback on catch technique. Although catch slip assessment via pre-determined force thresholds can be calculated by instrumentation systems enabling instantaneous feedback and therefore a more practically effective method of technical analysis (George, 2013; Lintmeijer, van Soest, et al., 2019), this measure is the least individualised of those discussed. The force threshold corresponding to boat propulsion can be expected to differ between individuals, and contradicting evidence exists as to how the selected force thresholds relate to boat velocity (Coker, 2010; Millar et al., 2015). Further, as this measure can provide a false-positive outcome where poor catch technique from missing water results in smaller catch slip values, force thresholds seem to be the least informative measure of catch slip, yet the most commonly used.

2.3.3.3 Force application at the oar: measurement and influence on performance

Most rowing instrumentation systems allow for quantification of rower force output over time or oar angle for a single rowing stroke – referred to as force-time and angle curves (Figure 2.5). Due to the multiple points of force application within the boat-rower system, force can be measured at the footplate, oar handle or gate via instrumentation systems, enabling each of these locations to provide differing insights into technical performance parameters. The propulsive force applied to the footplate and pin represent the net force applied to the boat by the rower, with force measured at the handle and gate providing insight into the application of force to the water to achieve forward propulsion of the boat. As the focus of this section is the impact of technical parameters on rowing performance, the measurement of force at the oar (handle and gate) will be discussed.

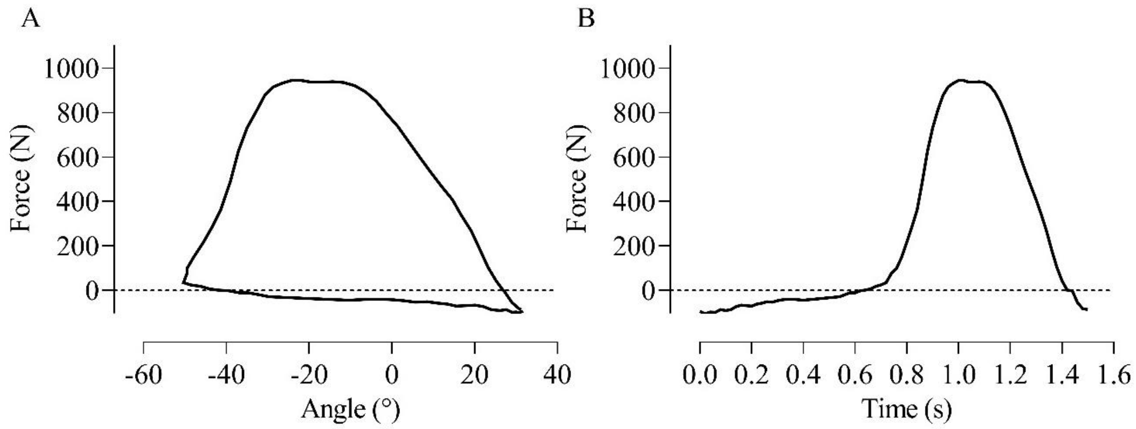

Figure 2.5 Force measured at the gate presented over angle (A) and time (B).

Force measured at the handle is achieved via instrumentation systems incorporating strain gauges attached to the oar shaft on the oar's inboard (Figure 2.6) which measure deflection of the oar throughout the stroke, allowing calculation of the moment of force applied at the handle (Kleshnev, 2010b). However, issues arise in the practicality of measuring force from the oar shaft as differences in flexion properties between oars of the same make and model mean calibration of each oar is required with recalibration following any change to inboard or outboard length.

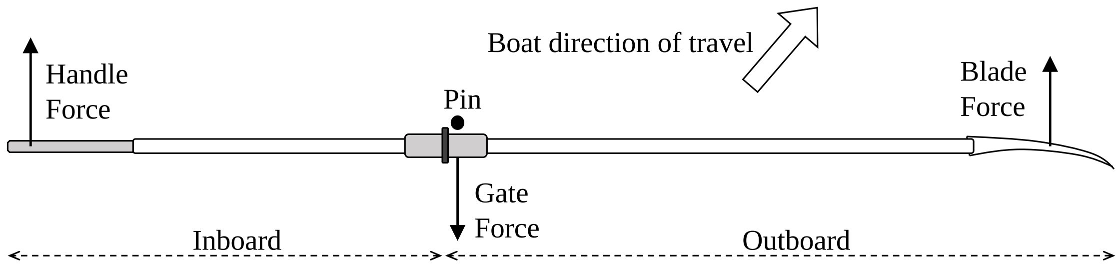

Figure 2.6 Free body diagram of forces acting on the oar.

Instrumentation systems located on the gate calculate handle force from force applied at the gate. Calculation of handle force requires knowledge of the oar angle, and the position of force application at the handle and blade. However, as the position of force application can't be assessed at the handle and blade (and can be expected to change within and between strokes) they are estimated using the inboard and outboard lengths, and are believed to equate to errors up to 5% (Kleshnev, 2010b).

Force curve shape is determined by a range of factors and provides both technical and physical performance insights. Force curves are presented either as force over time or angle, with area under the force-angle curve providing a measure of work done per stroke, enabling insight into crew set up and gearing differences between individuals. Similarly, area under the force-time curve provides a measure of impulse and allows comparison of stroke timing differences between individuals. Therefore, larger areas under the force curve correspond to greater applied impulse and resultant boat velocity (Coker, 2010). Force curve area is also a factor of curve smoothness, a parameter that appears to be enhanced in elite rowers via the reduction of dips in the force curve suggested to reduce within-stroke velocity fluctuations (R. M. Smith & Spinks, 1995). Although limited research has examined the relationship between measures of stroke force and boat velocity, large and very large positive relationships between stroke power (r = 0.60-0.88) and peak stroke force (r = 0.71-0.68) with boat velocity have been observed in two elite single scullers (Coker, 2010).

A triangular force curve, achieved via the occurrence of peak force when the blade is perpendicular to the boat's long axis, was originally believed to be advantageous as force applied in the direction of forward propulsion was maximised (Celentano, Cortili, Di Prampero, & Cerretelli, 1974; T. P. Martin & Bernfield, 1980). However, knowledge of lift forces occurring at the catch and consideration of force curve area favours a more rectangular curve shape, whereby the occurrence of peak force early in the drive via high rates of force development increases the impulse and subsequent boat velocity achieved during the drive for a given peak force magnitude (Figure 2.7) (Hume, 2018; Millward, 1987). The early occurrence of peak force achieves a more even distribution of power throughout the drive, reducing within-stroke boat velocity fluctuations and corresponding to a greater average boat velocity and distance per stroke (Kleshnev, 2006; Warmenhoven, Cobley, et al., 2017). Additionally, peak force generated early in the stroke maximises lift force at the catch (enhancing mechanical efficiency and propulsive force) and is suggested to exploit the elastic recoil of the oar shaft (Kleshnev, 2007). However, the propulsive contribution of oar elastic recoil has been questioned given the drag effect of water on the blade and dissipation of elastic energy as thermal energy (Laschowski, 2014). The return of elastic energy may occur later in the stroke at less efficient oar angles, limiting the propulsive contribution of the oar elastic recoil. Furthermore, less-stiff oars with greater deflective properties correspond with slower rates of force development likely delaying the occurrence of peak force (Laschowski, 2014).

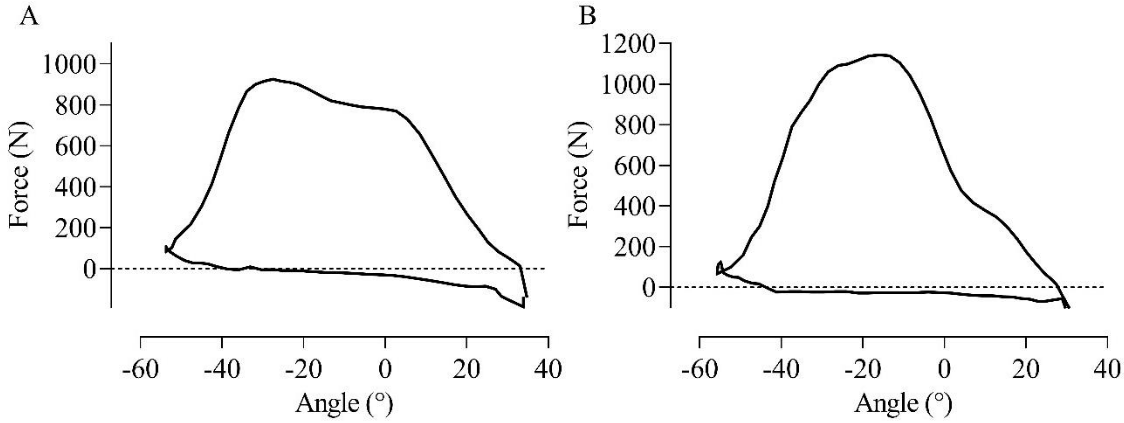

Figure 2.7 Force-angle curves from two rowers demonstrating rectangular (A) and triangular (B) shaped force curves.

Symmetrical force application between bow and stroke sides has previously been believed necessary to minimise drag forces arising from boat yaw, with differences in synchronicity between crew members suggested to be more detrimental to performance than differences in force curve area (Wing & Woodburn, 1995). However, differences in crew force synchronicity prove beneficial in coxless pair boat classes where an earlier and higher peak stroke force in stroke seat compared to that of the bow seat minimises boat yaw (R. M. Smith & Loschner, 2002; Zatsiorsky & Yakunin, 1991). Due to the asymmetrically rigged nature of the pair, force is applied at different positions relative to the boat's centre of rotation, resulting in differing rotational force moments acting on the boat from each rower, therefore the aforementioned discrepancies between bow and stroke seats act to minimise boat yaw (Coker, 2010). Furthermore, rower alteration in the location and magnitude of peak stroke force has been recorded when crew members have been changed in pair boats, while alterations to improve synchronicity between crew members has been observed, this does not explain rowing performance (Baudouin & Hawkins, 2004; Feigean, R'Kiouak, Bootsma, & Bourbousson, 2017).

Less is known regarding the effect of crew and oar side force synchronicity on performance in sculling boats. Due to inboard lengths, the handles cross over each other in the late drive, finish and early recovery phases of the stroke in sculling boats (Figure 2.3). The bow side gate is typically rigged ~10 mm higher to allow movement of the bow side handle over the stroke to avoid handle collision during rowing, however this results in upper body asymmetry with the right hand often leading the left during the drive and is expected to contribute to discrepancies in bow and stroke side force curve shapes observed in sculling (Draper & Smith, 2006). In comparison to national level rowers, international rowers have greater asymmetry of forces with stroke side force leading bow side through the first half of the drive and bow side force leading stroke side from mid-drive through to the finish (Warmenhoven, Smith, et al., 2017). Less negative bow side catch angles and greater finish angles have also been observed in international rowers, possibly counteracting the asymmetry arising from rigging differences through producing a more even force moment (Warmenhoven, Cobley, et al., 2017).

Asymmetry in force application between crew members in double sculls does not have the same performance benefit as in pairs. Investigation of crew force synchronicity in double sculls revealed differences between crew members in the location of peak stroke force was not related to boat velocity, leading the authors to suggest synchronisation of force curves does not benefit performance in crew sculling boat classes (Coker, 2010). Rather an earlier peak stroke force achieved by the stroke seat in comparison to that by the bow seat sculler is recommended to achieve a rectangular shaped crew average force profile, corresponding to a more even force application and subsequently minimised within-stroke boat velocity fluctuations (Coker, 2010; R. M. Smith & Loschner, 2002).

Seating order in crew sculling boats is another important performance consideration. Preliminary evidence supports a reduction in stroke force achieved in seats further towards the bow (Coker, 2010), possibly due to the faster movement of water near the bow and faster drive time resultant from a slight delay in timing throughout the crew. Conversely, alteration to seating order in double sculls has been found to influence prognostic boat velocity by up to 5.8% of the World's best time (Coker, 2010). Boat class is also a determining factor of force profile characteristics, with stroke power, stroke force and peak stroke force appearing to decrease between single scull and quadruple scull boat classes, likely explained by faster muscular contraction velocities in larger, faster boat classes relating to reduced muscular force producing capacity (Coker, 2010).

2.3.3.4 Validity and reliability of rowing instrumentation systems

Rowing instrumentation systems enable instantaneous feedback to the rower on a number of technical measures of rowing performance, including arc length, catch and finish angles, catch and finish slips, peak force and power output per stroke. Catch angles improved by 6% in highly-trained female rowers when the Peach PowerLine system was used to provide instantaneous oar angle feedback compared to post-row visual and verbal feedback (George, 2013). Furthermore, training intensity adherence has been shown to improve by 65% in rowers when instantaneous power output feedback was provided compared to boat velocity, stroke rate and coach feedback alone (Lintmeijer, van Soest, et al., 2019). These findings demonstrate the difficulty faced by rowers in complying with training intensity and technical targets where reliable instantaneous feedback is limited and allude to the potential benefits of instantaneous feedback via instrumentation systems on both technical and physical aspects of rowing performance.

Reliability and validity testing of force and angle measurement by commercially available rowing instrumentation systems are presented in Table 2.4 and demonstrates these devices to have acceptable precision and repeatability for angular measurements, however poorer reliability and validity for power and force measures considering the 1% smallest worthwhile change for rowing power output (T. B. Smith & Hopkins, 2011). The low reliability (1.9% TE) established for on-water stroke power is likely to weaken the relationship between stroke power and boat velocity given the high reliability of the later measure (0.59% TE) (Coker, 2010), making the performance impact of stroke power difficult to assess. Nevertheless, force profiles are highly repeatable irrespective of force output (Baudouin & Hawkins, 2004; Wing & Woodburn, 1995), demonstrating the difficulty associated in achieving technical adjustments related to force curve shape.

Table 2.4 Reliability and validity of commercially available rowing instrumentation systems

Authors	Rowing instrumentation system	Location of force measurement	Assessment protocol; participant characteristics	Reliability outcome	Validity outcome
Kleshnev (2017)	EmPower vs. BioRow	Gate (EmPower) Handle (BioRow)	Concurrent validity testing over 2000 m		*r* = 0.997 stroke rate *r* = 0.904 power *r* = 0.881 catch angle *r* = 0.937 finish angle *r* = 0.929 total angle *r* = 0.934 catch slip *r* = 0.578 finish slip *r* = 0.832 average force *r* = 0.828 max force *r* = 0.889 max force angle
Laschowski & Nolte (2016)	Peach PowerLine	Gate	Static application of 0, 32.5, 255.1, 431.6 N unidirectional forces	p = 0.335 (scull) p = 0.451 (sweep) maximum change in mean: 4.3% ± 2.6 pp (sweep) 3.9% ± 1.4 pp (scull)	-2.0% ± 0.8 pp median difference Maximum difference: 4.5% ± 1.6 pp; 15 ± 4 N (scull) 3.3% ± 1.5 pp; 14 ± 7 N (sweep) $R^2 \geq 0.999$ *r* = 0.986 ± 0.005 (sweep) *r* = 0.985 ± 0.005 (scull)
Coker (2010)	Peach PowerLine	Gate	3 x 500m trials under race conditions; 6 x elite (3 F, 3 M)	Power SEE: 4.3-4.5% Catch angle SEE: 0.6-0.7% Finish angle SEE: 0.7-0.8% Catch slip SEE: 0.7%	

				Finish slip SEE: 0.9-1.0% Power TE: 1.3-2.2% Catch angle TE: 0.2-0.4° Finish angle TE: 0.2-0.4° Catch slip TE: 0.2-0.3° Finish slip TE: 0.2-0.4°	
Coker, Hume, & Nolte (2009)	Peach PowerLine	Gate	Dynamic linear force application at 30 strokes·min^{-1} across 0.0 N to 554.8 ± 20.4 N; -80° to +60°		SEE: 7.16 ± 2.56 N SEE: 0.9 ± 0.9° Maximum SEE: 11.7 N Maximum SEE: 3.1° R^2 = 0.999 force R^2 = 1.00 angle
Draper & Smith (2006)	Unspecified	Gate	250m @ 20, 24, 28, 32 strokes·min^{-1}; 12 F highly trained	Angle: 0.5 ± 0.3% CV Force: 2.7 ± 2.0% CV	
Soper, Hume, & Tonks (2003)	RowBot	Gate	5 x 60 s; 11 elite (2 M, 9 F)	TE arc length: 1.2% 0.08-2.2 (95% CL) TE peak force: 4.9% 6.7-17.8 (95% CL) *r* > 0.90 between trials in stroke force, peak force, angle at peak force, arc length, catch and finish angle	

r (correlation coefficient); scull (sculling gates); sweep (sweep gates); pp (percentage points); M (male); F (female); SEE (standard error of the estimate); TE (typical error); ICC (intraclass correlation coefficient); strokes·min^{-1} (stroke per minute); R^2 (variance explained); ^{CV} (coefficient of variation); CL (confidence limits); stroke force (average force produced across the drive phase of one stroke

Validity testing of commercially available rowing instrumentation systems has previously encompassed static (Laschowski & Nolte, 2016) or dynamic linear force application (Coker et al., 2009) not reflective of a rowing-specific pattern of force application. Therefore, the applicability of results from validity and reliability studies to on-water rowing is unknown, particularly considering the sensitivity of rowing instrumentation systems to the point of force application on the device (Laschowski & Nolte, 2016). Furthermore, validity testing of power measurement by these devices has only been conducted on the Nilsen-Kellerman EmPower (Kleshnev, 2017) and further testing is required to establish the reliability and validity of this device against a true criterion measure rather than another rowing instrumentation system, as previously used. Finally, research investigating the difference between power calculated from applied forces at the pin and force calculated using the rower's centre of mass, its acceleration, and boat velocity reveals underestimation of mechanical power by 12.3 ± 1.1% by gate-based instrumentation systems (Hofmijster, 2010), highlighting the importance of considering force and power output with respect to measures of rowing performance such as boat velocity.

2.3.3.5 Boat velocity and acceleration fluctuations: measurement and influence on performance

Boat velocity fluctuations within the rowing stroke occur due to disharmony between centre of mass acceleration of the rower and that of the boat, which translate to within stroke acceleration fluctuations of the rower-boat system. These fluctuations can be measured using an accelerometer, typically in combination with a GNSS but are also included in the Peach PowerLine rowing instrumentation system. Acceleration profiles reflect the shape of their corresponding force curves ($R^2 = 0.904$) (Draper & Smith, 2006), with force generated during the drive contributing to acceleration of the rower-boat system (Kleshnev, 2010a).

Typical boat acceleration and velocity curves are shown in Figure 2.8 illustrating a negative peak in boat acceleration and accompanying reduction in boat velocity occurring immediately following the catch where sternward directed force is applied to the foot stretcher and blade entry increases drag forces on the shell. Following the catch an immediate steep increase in acceleration occurs as the blade completes entry into the water in coordination with acceleration of the rower's centre of mass, however the acceleration of the boat's centre of mass is lower than that of the rower and remains negative while boat velocity is at its lowest at this point. Acceleration of the boat's centre of mass become positive and peaks in the early drive phase as leg drive is maximised translating to acceleration of the boat overtaking that of the rower's centre of mass, corresponding to a steady increase in boat velocity. The size of this initial acceleration peak and the steepness of the acceleration curve immediately preceding it relate directly to boat velocity, with higher peaks and steeper curves achieved by maximising rower centre of mass acceleration and accumulating kinetic energy in the early drive and mid-drive phases via achieving high foot stretcher forces, and maximising boat acceleration in the late drive via emphasis of handle force through trunk and arm force contributions (Kleshnev, 2010a). A subsequent dip in boat acceleration is visible with faster acceleration of the rower's centre of mass as leg velocity decreases towards the end of the leg drive phase. A second peak is observed in boat acceleration mid-drive as leg drive transitions into trunk swing, foot stretcher force is reduced with maintenance of force on the handle at this point resulting in the highest boat acceleration achieved during the stroke. A decrease in boat acceleration close to zero and levelling off of boat velocity is observed as blades are withdrawn from the water at the finish corresponding with negative acceleration of the rower's centre of mass. A successive positive peak in acceleration occurs following the finish due to transfer of momentum from the rower to the boat during the early recovery phase. Finally, drawing of the foot stretcher towards the rower during the recovery acts to pull the boat in the direction of travel, contributing to the highest boat velocity achieved during the stroke and a corresponding positive peak in boat acceleration (Kleshnev, 2010a).

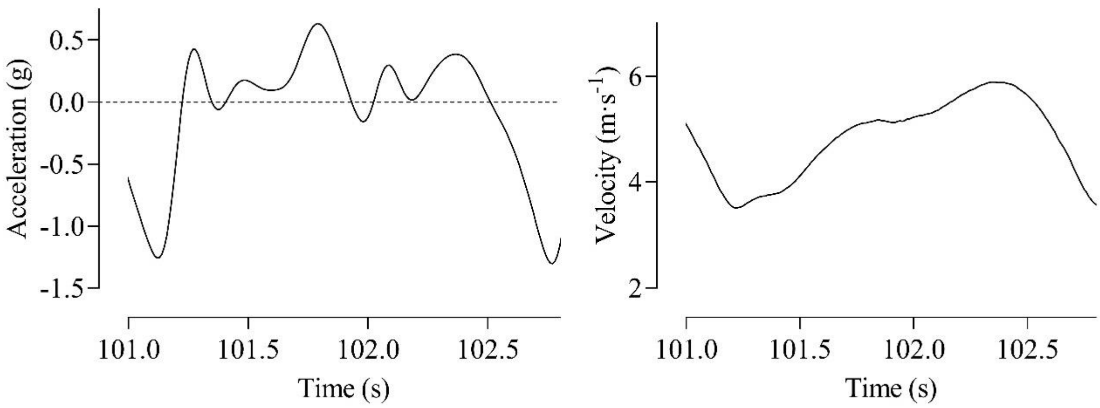

Figure 2.8 Acceleration (left) and velocity curves (right) over one stroke from a men's single scull.

Fluctuations of boat velocity throughout the rowing stroke affect water flow in the boundary layer surrounding the hull, increasing the drag acting on the boat (Greidanus, Delfos, & Westerweel, 2016). As such, large within-stroke boat velocity fluctuations should be avoided due to the resultant reduction in velocity efficiency (ratio of propulsive power to the minimum power required to achieve the same average boat velocity), particularly given the metabolic cost of rowing is estimated as boat velocity$^{2.4}$ (Secher, 1993). This is supported by findings from the sliding wing rigger boat which was prevalent in the early 1980s but has since been banned from international racing by the governing body of rowing, FISA. The boat encompassed a stationary seat whereby force was applied to a moveable foot stretcher and rigger, reducing within-stroke velocity fluctuations due to minimising rower centre of mass movement with respect to the boat, and has been calculated improve 2000 m race time by 2.1 s (Hill & Fahrig, 2009).

Effective acceleration of the rower's centre of mass at the catch is another factor associated with enhanced boat velocity. Successful international rowers demonstrate much larger negative acceleration peaks at the catch than national level rowers (-10.1 and -6.9 $m \cdot s^{-1}$ respectively), however the duration of these negative peaks are much shorter in international rowers (0.48 s) than national levels rowers (0.59 s), reflecting quicker acceleration of rower centre of mass and therefore the rower-boat system at the catch (Kleshnev, 2002). Effective acceleration of the rower's centre of mass at the catch can also be quantified by the absence of a loop at the catch when boat acceleration is presented over angle, representing application of force at the handle prior to foot stretcher force and the occurrence of negative peak acceleration (Coker, 2010).

The magnitude of within-stroke boat velocity variation demonstrates very large relationships with stroke rate (r = 0.98) (Hill & Fahrig, 2009). Variations in boat velocity of 11.7% and 13.7% have been calculated to occur within the stroke at 20 and 40 $strokes \cdot min^{-1}$ respectively, contributing to a 1.46% reduction in velocity efficiency and 1.5 s time loss over 2000 m (Kleshnev, 2007). A very large negative relationship (r = -0.72) exists between velocity efficiency and stroke rate (Hofmijster, Landman, Smith, & Knoek Van Soest, 2007), which is further explained by the calculated time loss of 4.59 s at 24 $strokes \cdot min^{-1}$ and 5.05 s at 32 $strokes \cdot min^{-1}$ due to within-stroke velocity fluctuations in comparison to a boat moving with constant velocity over 2000 m (Hill & Fahrig, 2009). The negative peak of boat acceleration at the catch also demonstrates a very large relationship with stroke rate (r = -0.85 to -0.88), as does within stroke acceleration fluctuations (r = 0.93), whereas the initial positive acceleration peak is less effected by stroke rate (Hill & Fahrig, 2009; Kleshnev, 1998, 2010a). These findings are related to the rower's centre of mass moving faster through the recovery phase to achieve higher stroke rates, generating greater inertial forces and subsequent velocity fluctuations given the very large relationship between within-stroke boat acceleration and velocity fluctuations (r = 0.96) (Hill & Fahrig, 2009). Raised foot stretcher heights have been found to increase the negative peak of boat acceleration by 0.41 $m \cdot s^{-1}$, reduce within-stroke velocity fluctuations by 0.16% and increase boat velocity by 0.12 $m \cdot s^{-1}$ (Liu et al., 2020). Recovery phase duration is recommended to be maximised with reductions to drive phase duration, reducing the drive-to-recovery ratio in order to mitigate large fluctuations in rower acceleration and within-boat velocity fluctuations (Baudouin & Hawkins, 2004; Kleshnev, 1998, 2002). Similarly, boat velocity increments are recommended to be achieved via increasing stroke force with a moderate reduction to stroke rate, however this will achieve only small improvements in boat velocity consistency and overall race time in skilled rowers (Hill & Fahrig, 2009). Nevertheless, the impact of acceleration characteristics and within-stroke velocity fluctuations on average boat velocity warrants the consideration of these factors in the assessment of rowing performance.

2.3.4 Summary of current measurement practices of rowing performance

Current measurement practices use boat velocity and race time as predominant measures of rowing performance. However, issues arise given the poor reliability of velocity measures where environmental conditions vary, reducing the sensitivity of these measures in detecting true changes in rowing performance. Stationary rowing ergometers are also commonly used in high-performance rowing programs to assess physiological rowing capacity. However, important technical and performance differences exist between on-water and ergometer rowing, reducing the specificity of ergometer-based rowing performance testing.

Instrumentation systems have been used in rowing to quantify technique, providing insights into the impact of catch and finish angles, catch and finish slips, force and acceleration curve shapes, and within-stroke boat velocity fluctuations on rowing performance. However, more research is required to determine the relationships between these measures of rowing technique and boat velocity across a population of rowers. Rowing instrumentation systems may overcome the limited reliability of boat velocity for assessing overall rowing performance where environmental conditions vary, as environmental conditions are expected to have very little influence on rower power output. Furthermore, the assessment of rower power on-water enabled by the use of instrumentation systems would overcome the reduced specificity of ergometer-based physiological and performance assessment. Finally, instrumentation systems may be used prospectively for the assessment of race demands, performance modelling, and pacing analyses in rowing as they have been in other sports, as discussed in further detail in section 2.4.

2.4 Applications of instrumentation systems in other sports and their prospective use in rowing

2.4.1 Validity testing of instrumentation systems in other sports

Instrumentation systems, or commonly referred to as power meters, first became commercially available in cycling in 1989, since then their use has evolved to be a habitual method of training load quantification and performance monitoring at both elite and amateur levels. Various types of cycling power meters are available that calculate power from strain measured in the crank set (Schoberer Rad Meßtechnik [SRM], Jülich, Germany; Stages, CO, USA; and 4iii, AB, Canada), rear wheel hub (PowerTap, CycleOps, Madisson, USA and Max One, Look, Cadex, France), and pedal axles (Keo, Look, Cadex, France). The nature of cycling power meters allow validity testing to take place on a cycling ergometer where a known torque and angular velocity can be delivered to the pedal shaft axis via a dynamic calibration rig acting as a criterion measure of power (Woods, Day, Withers, Ilsley, & Maxwell, 1994).

The SRM is considered a valid and reliable commercially available cycling power meter, however, reasonable error in this device has been observed in comparison to calibration rigs. The SRM demonstrates good validity against a dynamic calibration rig at constant power outputs of 250 and 414 W with no significant differences between the SRM and calibration rig and typical error values of 0.18 and -0.05% respectively (Abbiss, Quod, Levin, Martin, & Laursen, 2009). When calibrated to within 2% of calibration rig power and following 11 months of use SRM devices demonstrated little deviation in power output (0.8 ± 1.7%) in comparison to the calibration rig when retested (Gardner et al., 2004). However, the same study observed SRM errors of 2.3 ± 4.9% (mean ± SD) in comparison to calibration rig power when 50-1000 W was applied over 60 s intervals (Gardner et al., 2004). The SRM also underestimated average power output by 2.6% compared to a calibration rig when assessed over 35 s intervals ranging from 0-1700 W of applied power (Abbiss et al., 2009). In addition, the SRM appears to be influenced by temperature, with errors of up to 5.2% observed when tested in 6 °C.

The SRM has also been used to assess the concurrent validity of other cycling power meters. The PowerTap measured 1.2 ± 1.3% lower power outputs between 100-420 W compared to the SRM, with up to a -8% difference during 8 s maximal efforts where low gear ratios were used (Bertucci, Duc, Villerius, Pernin, & Grappe, 2005). Similar reliability has also been established for the PowerTap (1.8 ± 0.6% CV) and SRM (1.5 ± 1.4% CV) at power outputs between 100-420 W. The ErgomoPro (Bellati Sport, Switzerland) power output was 6.3 ± 2.5% higher than the SRM over 100-400 W, 12 ± 5.7% higher during 180 minutes of field testing at 140 W, and 1.6 ± 2.5% higher during 8 s maximal tests. No statistical difference was found between Keo power pedals and SRM during 10 s maximal tests (14.2 W lower power output measured by the Keo) and submaximal cycling over 75-1147 W (1 W lower power output measured by the Keo) (Sparks, Dove, Bridge, Midgley, & McNaughton, 2015). Validity testing reveals power output to be more reliable when tested using power meters attached to participants' bicycles rather than cycle ergometers, possibly due to the familiarity of participants with their own bicycle (Hopkins et al., 2001). Nevertheless, due to the popularity of power meters in cycling many new brands have become commercially available, for which peer-reviewed validity research is yet to be published.

Instrumentation systems have also more recently been introduced in flatwater kayak paddles, with the placement of strain gauges around the paddle shaft measuring torque in the shaft as force is applied at the handles. To date just one brand of kayak instrumentation system is commercially available (One Giant Leap, New Zealand) and has been validated for force output with differences of 0.12-1.4% observed between the instrumentation system and 51.5, 102.5, and 155.9 N of statically hung weights from the paddle shaft, with good reliability (0.12-1.48% CV) for the repeated testing of these forces (Macdermid & Fink, 2017). However, as with rowing instrumentation systems, the validity of power output from kayak instrumentation systems is yet to be established, as is the validity of force measurement for sport-specific modes of force application.

2.4.2 The use of instrumentation systems for performance modelling and pacing analysis in cycling

Performance modelling encompasses calculation of the power output required to achieve a specific time over a given time trial distance while adjusting for factors that impact performance. Performance modelling has been predominantly used in track cycling given the consistent nature of conditions in an indoor track enabling the calculation of power required to achieve a given performance outcome (Bassett, Kyle, Passfield, Broker, & Burke, 1999; Lukes, Hart, & Haake, 2012; Lukes R, M, & S, 2006; Olds, Norton, & Craig, 1993; Schumacher & Mueller, 2002a; Underwood & Jermy, 2010). The performance effects of wind resistance, ground surface resistance, wheel characteristics, rider mass and frontal surface area, temperature, humidity, air density, rider clothing including helmet shape, and rider position include some of the factors used to predict the power output required to achieve a given velocity and resultant race time, with each of these factors typically awarded a correction factor in the calculation of cycling velocity (Bassett et al., 1999; Di Prampero, Cortili, Mognoni, & Saibene, 1979; Faria, Parker, & Faria, 2005; Jeukendrup & Martin, 2001; J. C. Martin, Milliken, Cobb, McFadden, & Coggan, 1998; Olds et al., 1995; Schumacher & Mueller, 2002a).

Studies investigating performance modelling have found similar performance results between that modelled and measured, in both indoor and outdoor environments. When used to estimate the power output required throughout a 4000 m team pursuit race to break the World record, performance modelling contributed to the resultant successful record attempt (Schumacher & Mueller, 2002a). Performance modelling has also been investigated in road cycling to determine if time trial performance can be predicted where conditions are less constant than track cycling. Martin et al. (1998) assessed power output from six trained male cyclists over a 472 m flat course at velocities between 7-11 $m \cdot s^{-1}$ in comparison to power output calculated from a mathematical model (J. C. Martin et al., 1998). Power calculated by the model and that measured by SRM power meters during time trials was not statistically different, with a 2.7 W SEM and an extremely large correlation (R^2 = 0.97) found between modelled and measured power (J. C. Martin et al., 1998). Performance modelling has also been used to predict time trial time over a flat 26 km course in 41 male and female cyclists (Olds et al., 1995). Modelled and measured performance time had a very large correlation (*r* = 0.89) with a 0.74 ± 2.07 minute (mean ± SD) difference in time trial time observed. These studies highlight the ability to predict time trial performance in environments where conditions are not constant, and therefore the possibility of power-based performance modelling in rowing. However, the effects of wind resistance (Filter, 2009; Kleshnev, 2009), stream flow conditions, water turbulence (i.e. waves), hull shape and wet area, blade shape (Caplan & Gardner, 2007a; Robert et al., 2019), boat class (Coker, 2010), as well as rigging and oar length on rowing power output and boat velocity must also be considered.

The effects of different pacing strategies on cycling time trial performance has been investigated using performance modelling (Gordon, 2005; Wells, Atkinson, & Marwood, 2013). Variations in power output of 5, 10, and 15% of mean power were modelled over 4, 16.1, 20 and 40 km time trial distances with findings indicating slower performance times when power is varied in time trials longer than 16 km in comparison to constant power outputs (Wells et al., 2013). Performance was impaired by a greater extent with larger magnitudes and durations of power variation. Performance time was extended by 3.19 s and 7.97 s with 10% and 15% variations in power over 1.25 km periods during the 40 km time trial, which increased to impairments of 4.26 s and 10.43 s respectively when the period of power variation was extended to 20 km (Wells et al., 2013). However, variations in power in the form of a fast-start pacing strategy enhanced performance time in the 4 km time trial compared to a constant power strategy, with variations of 15% improving time to a greater extent (0.84 s) than smaller 5% power variations (0.42 s) (Wells et al., 2013). The performance benefits of a fast-start pacing strategy are also supported by research in well-trained cyclists over 1500 m time trials and kayakers during 2 min time trials (Bishop, Bonetti, & Dawson, 2002; Hettinga, De Koning, Hulleman, & Foster, 2012). Faster performances have been found when cyclists performed a fast-start strategy compared to a more evenly paced strategy, with the fastest performance times found to have greater anaerobic peak power (828.8 ± 145.4 vs 649.5 ± 112.2 W) and aerobic power (295.3 ± 36.8 vs 287.5 ± 34.7 W) than the slowest times, leading the authors to suggest the effect of accelerated oxygen kinetics benefitting fast-start strategies (Hettinga et al., 2012).

Pacing strategies in rowing traditionally employ fast-starts (Garland, 2005; Kleshnev, 2016; Kleshnev & Nolte, 2001; Renfree, Martin, Richards, & St Clair Bibson, 2012) which may be explained by the duration of the event (2000 m; ~5.5-7.5 min) given the benefit of a fast-start strategy in shorter time trial events in cycling (Hettinga et al., 2012; Wells et al., 2013). However, a more even-paced race strategy may be more beneficial in rowing given the considerable frictional resistance of water and the cubed relationship between power and boat velocity (Zatsiorsky & Yakunin, 1991) contributing to greater velocity losses for a given reduction in power output in comparison to cycling. Analysis of rowing performance time with respect to variations in power output throughout a race would therefore be beneficial in determining favourable pacing strategies in rowing.

2.4.3 Summary of the applications of instrumentation systems in other sports

This section has described the types of instrumentation systems available in other sports (namely cycling and flatwater kayak), their validity, reliability and use in race performance assessment, performance modelling and pacing analysis in cycling. The implementation of power meters in cycling specifically has furthered their application in the sport, opening the door to effective race analysis and, quantification of race demands, and the calculation of the power output required to achieve success. The research encompassing power meters in cycling is largely transferable to rowing, indicating promise for the application of instrumentation systems in rowing. The implementation of instrumentation systems in rowing can be expected to solve the issues currently associated with quantifying training and racing performance in rowing (specifically the influence of environmental factors and the reduced specificity of ergometer rowing), and the assessment of race demands. In addition to their applications in cycling, rowing based instrumentation systems provide a means of quantifying rowing technique and its contribution to overall rowing performance, reflecting their potential as a comprehensive measure of rowing performance.

2.5 Conclusion

This literature review has discussed current measurement practices for the assessment of rowing performance and discussed what is known with regard to the factors contributing to rowing performance. Rowing instrumentation systems provide a comprehensive measure of rowing performance, enabling the assessment of rowing technique as well measures of power and stroke rate. Measures of power from rowing instrumentation systems may provide more a more reliable tool for assessing rowing performance than the more predominantly used measures of rowing velocity or race time due to the difficulty in detecting true changes in rowing performance in varying environmental conditions with these measures. However, the validity of reliability and criterion validity testing has only been conducted in one commercially available device (Peach PowerLine) and over linear force and angle applications non-specific to rowing (Coker et al., 2009; Laschowski & Nolte, 2016). The validity of neither power output nor catch and finish angles have been assessed in any rowing instrumentation system currently available on the market. Therefore, before rowing instrumentation systems can have a practical impact in performance assessment the validity of commercially available devices must first be established.

Determinants of rowing performance have largely been explored in ergometer-based rowing, where maximal aerobic capacity, peak power, and leg strength have been found to have large relationships with ergometer performance. The literature describes catch and finish angles, catch and finish slips, patterns of force application, and within-stroke fluctuations in boat acceleration as key factors of rowing performance. However, little research has investigated relationships between measures of rowing technique or boat acceleration with on-water rowing performance, with current research limited to small sample sizes and revealing opposing findings. Furthermore, the contribution of rowing technique to overall rowing performance has not been examined.

Finally, the prospective use of instrumentation systems in rowing is exemplified by their use in cycling. Research encompassing the use of instrumentation systems in cycling is largely transferable to rowing, illustrating their potential widespread value. This includes the analysis of race demands, establishments of contributing factors to race performances, directing training focusses, informing race tactics, and enabling performance monitoring via power-based benchmarks. However, research regarding the use of rowing instrumentation systems in this context has yet to be undertaken.

Chapter Three: Concurrent validity of Peach PowerLine and Nielsen Kellerman EmPower rowing instrumentation systems for measurement of oar angles

3.1 Abstract

Purpose: Validity of rowing instrumentation systems for oar-angle measurement has only been assessed statically. In this study the concurrent validity of Peach PowerLine and Neilsen-Kellerman EmPower devices was investigated for catch, finish, and arc angle detection against a Vicon motion analysis system during simulated on-water rowing. **Methods:** Three Peach and four EmPower units were assessed through a range of submaximal and maximal stroke rates with one experienced rower. Mean and between-unit differences for systematic error and random error effects for Peach and EmPower were estimated with general linear mixed modelling. Effects were interpreted using superiority and inferiority testing with a smallest important angle of 0.5°. **Results:** Systematic error was mostly unclear and trivial-small for catch and finish angles in Peach and EmPower, trivial-small for arc angle in EmPower, and small-moderate and decisively substantial for arc angle in Peach. Between-unit differences in systematic error were mostly unclear; observed differences for Peach were moderate for catch and finish angles, and small for arc angle; for EmPower, they were small-moderate for catch and finish angles, and mostly large for arc angle. Magnitudes of random error were almost all decisively substantial: in Peach, small for catch and arc angles, and trivial-small for finish angle; in EmPower, mostly extremely large for catch and arc angles, and mostly moderate for finish angle. Vicon random error was negligible (<0.1°). **Conclusion:** concurrent validity for oar-angle detection of individual strokes was acceptable for Peach but not for EmPower, owing to its random-error magnitudes.

3.2 Introduction

Catch, finish and arc oar angles are commonly assessed by coaches and sport scientists, as they provide valuable measures of rowing technique. Propulsive work during the drive is a product of the arc rowed through and force applied, therefore greater arc angles are desirable (Warmenhoven, Cobley, Draper, & Smith, 2018). Further advantages of larger arc angles are a result of horizontal lift forces occurring at catch angles less than -50° and finish angles greater than 20°, where the blade acts as a hydrofoil moving through the water in the direction of boat movement (Pulman, 2005; Robert et al., 2019).

Gate-based instrumentation systems can be used to assess catch, finish and arc oar angles. The measurement of oar angle is achieved through the swivel of the gate on top of stationary baseplate, instrumented with a potentiometer (Peach PowerLine, Peach Innovations, Cambridge, UK) or magnetic sensor (EmPower, Nielsen-Kellermen, Boothwyn, PA). Strain-gauge load cells positioned around the gate's inner tube also allow the measurement of resultant force at the gate. These devices provide instantaneous in-boat feedback quantifying catch, finish, and arc angles to rowers, which has been shown to increase rower catch angle attainment by 6%, compared to post-row visual and verbal feedback (George, 2013). Therefore, these devices appear to benefit the achievement and maintenance of technical changes in rowers.

Peer-reviewed research regarding the validity of oar angle measurement by commercially available instrumentation systems is needed, given knowledge in this area is lacking. Concurrent validity testing of EmPower and BioRow Tel (BioRow Ltd, Slough, UK) instrumentation systems revealed the devices to have large correlations for catch angle (r = 0.88), finish angle (r = 0.94), and total arc length (r = 0.93) (Kleshnev, 2017). However, these are unpublished findings, and no peer-reviewed research has investigated the validity of either of these devices. The validity of eight Peach sculling units for static angle measurement was tested through a range of -80° to 60° in 20° increments, against an inclinometer; the standard error of the estimate, representing device random error, ranged from of 0.2 to 3.1°, with a mean of ~0.6° across the units (Coker et al., 2009). However, the static testing of angle measurement does not reflect on-water demands of catch and finish angle measurement, where dynamic oar change of direction occurs following oar handle angular velocities of up to 125 $°\cdot s^{-1}$ during the drive phase (Feigean et al., 2017).

Reliability of catch and finish angles has been assessed in on-water rowing. Testing of Peach in six elite scullers over 40 strokes within a 500-m trial at 33 min^{-1} revealed within-rower stroke-to-stroke standard deviations of 0.5-1.0° for catch angle, and 0.6-1.5° for finish angle (Coker, 2010). However, the contribution of device random error to this variability is not known. Therefore, the aim of this study was to assess the concurrent validity of Peach PowerLine and Nielsen-Kellerman EmPower sweep rowing devices with a Vicon motion analysis system (T-40 series, Vicon Nexus v2.7, Oxford, UK) in a dynamic, on-water rowing-specific range of motion, for the quantification of catch, finish, and arc oar angles.

3.3 Methods

3.3.1 Participant

A female lightweight rower (age 27 y; height 168 cm; body mass 59.8 kg) with 10 y experience rowing at a national level volunteered for this study. The participant provided informed consent prior to commencement of the study. The study was approved by the University ethics committee.

3.3.2 Equipment

All rowing was performed on port-(stroke) side of a Swingulator team sweep trainer (Rowing Innovations Inc., Williston, VT) with Concept2 ergometer (Model E, Concept2 Inc., Morrisville, VT) attachment enabling the simulation of on-water sweep rowing with a fixed stretcher in a controlled environment (Figure 3.1). Oar inboard (distance between oar handle and collar) and total lengths were 114.5 cm and 177 cm respectively, with span (distance between the pin and the centre of the hull) 84.3 cm, these measurements were consistent throughout the study.

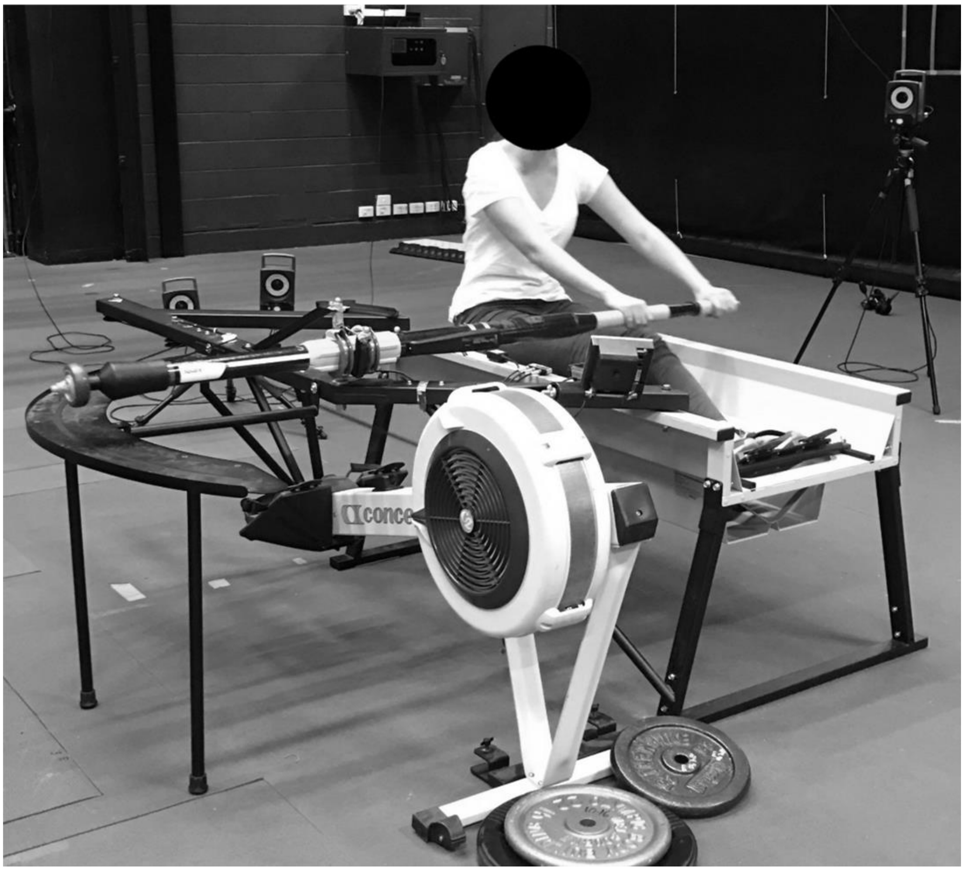

Figure 3.1 Image of Swingulator team sweep trainer with Concept2 attachment.

Validity testing of catch, finish, and arc angle detection was performed in six Peach (Peach Innovations, Cambridge, UK) and four EmPower (Nielsen-Kellermen, Boothwyn, PA) sweep units. Units were attached to the Swingulator's pin, replacing the gate. A Speedcoach GNSS Model 2 with Training Pack (Nielsen-Kellermen, Boothwyn, PA) was used as the EmPower receiver unit, where oar inboard and total lengths were entered. Peach logger box (receiver unit) settings will not allow total oar lengths to be entered as less than 200 cm, on consultation with the manufacturer inboard and total oar lengths were set to 129.4 cm and 200 cm respectively to reflect an equivalent inboard-to-total length ratio. A goniometer (EZ Read, Jamar, Performance Health, IL, USA) and straight-edge were used to set Peach and EmPower unit baseplates 90° to the Swingulator's hull. Calibration of gate angle to 0° (90° to the Swingulator's hull) was achieved using the goniometer and straight-edge. An additional angle calibration procedure was performed for EmPower devices using a gate angle calibration tool attachment (provided by the manufacturer) allowing the gate to be set to four known angles, then moved through several rotations of 0-180°. Force was calibrated via zeroing devices with the oar removed from the gate. Both force and angle calibration procedures were conducted as per manufacturer instructions and were performed prior to each trial. AA lithium batteries were used in all EmPower units, as per manufacturer recommendations.

A fourteen-camera Vicon motion analysis system (T-40 series, Vicon Nexus v2.7, Oxford, UK) set-up in an arc surrounding the Swingulator was used to assess the concurrent validity of the Peach and EmPower for catch, finish, and arc angles. Five 14 mm diameter reflective markers were attached to the Swingulator oar and gate, marker positions are presented in Figure 3.2. Vicon calibration was performed prior to each testing day.

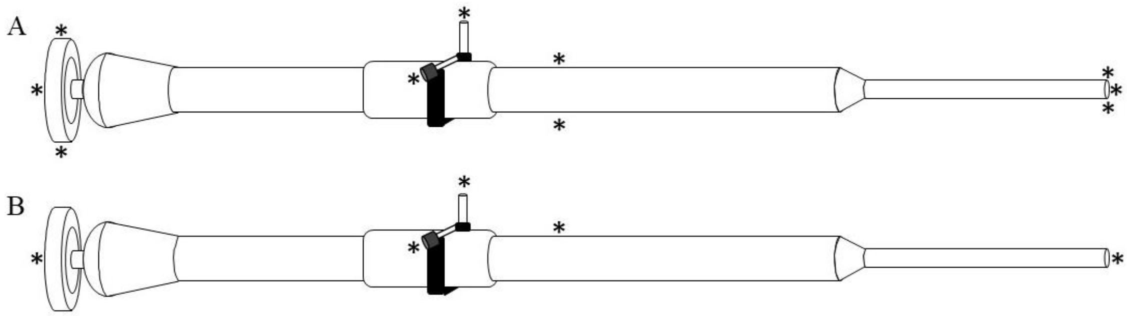

Figure 3.2 Free body diagram illustrating reflective marker position (*) on the Swingulator oar and gate during dynamic (A) and static (B) trials.

3.3.3 Study design

The participant performed several 30-minute familiarisation sessions on the Swingulator prior to the study. The study was conducted in a temperature-controlled laboratory (21.7 ± 0.4°C; 34.5 ± 2.6% RH). The participant completed 10 trials over a three-day period. Each trial consisted of 17 sets of 20-25 strokes, each set of strokes was performed at a single stroke rate between 16 to 44 min^{-1} in increments of 2 min^{-1}, including two 10-stroke maximal stroke rate efforts. These stroke rates cover the range of rates performed in training and competition. Stroke rate order was randomised per trial to mitigate any effect of stroke rate change. Catch and finish angles were recorded concurrently by Vicon and either Peach or EmPower units. Each trial tested one Peach or EmPower unit, with each unit tested once in a randomised order.

3.3.4 Data analysis

Raw Vicon data was collected using Nexus (version 2.7, Vicon, Oxford, UK) and processed in Visual 3D (version 6.3, C-motion, Inc. Germantown, USA). In the case of marker drop-out, the missing marker's position was modelled using the position of a nearby marker. A low-pass 4th order Butterworth filter with 6 Hz cut-off frequency was applied (cut-off frequency based on residual analysis, visual inspection of raw and smoothed curves and theoretical considerations of the low-frequency movement [i.e., the fastest stroke rate of 44 stroke·min^{-1} being less than 1 Hz]). A static trial including five additional reflective markers was used to create a 3-dimensional oar model (Figure 3.2) from which the oar angle was computed relative to the Vicon's y-axis (which was set as perpendicular to the Swingulator's hull) in the horizontal plane. Catch angle was defined as the largest negative angle achieved prior to the start of the drive (propulsive) phase of each rowing stroke, whereby an oar angle of zero degrees occurred when the oar shaft was perpendicular to the long axis of the Swingulator's hull. Finish angle was defined as the maximal positive oar angle achieved prior to the start of each recovery (non-propulsive) phase. Arc angle was calculated as the difference between catch and finish angles and provided a measure of the total angle rowed through during one stroke cycle. Catch and finish angles per stroke from Peach and EmPower units were exported to Microsoft Excel. Arc angle was calculated as the difference between catch and finish angles from Peach and EmPower exported data.

3.3.5 Statistical analysis

The general linear mixed-model procedure (Proc mixed) in the studio version of the Statistical Analysis System (version 9.4, SAS Institute, Cary NC) was used to assess concurrent validity of Vicon, Peach and EmPower. Systematic error between Vicon and Peach or Empower, random error within Peach and EmPower, and differences between Peach and EmPower units in systematic error and random error were estimated from various models. Separate analyses were performed for each of four stroke-rate bands: 16-28 min^{-1} (eight levels), 30-36 min^{-1} (four levels), 38-44 min^{-1} (four levels), maximal (two levels), and for each of the catch, finish, and arc angles. For estimation of population systematic error, fixed effects were device (Peach, EmPower, and Vicon), stroke rate, and stroke number (20-25 levels for sub-maximal stroke rate efforts, 10 levels for maximal stroke rate efforts). Random effects in the model were serial number (identifying the six

Peach and four EmPower units, to estimate the SD representing differences in systematic error between units); trial identity (to account for differences in overall mean angle for each trial from Vicon measurements); the interaction of stroke number, stroke rate, and trial (to account for the participant's stroke-to-stroke variation in angle), and the residual (separate estimates for each unit and for Vicon). The use of serial number as a random effect allowed estimation of mean error for each unit to be treated as a sample of means from the population of units. Mean error in the population of Peach or EmPower was provided by the fixed effect for device, which estimated the difference between the population mean for Peach or EmPower and the Vicon mean. Preliminary analyses revealed random error for Vicon to be negligible (generally much less than 0.1°). However, the large difference in Vicon residual error with that of Peach and EmPower appeared to occasionally produce convergence problems with the mixed model. To achieve consistent convergence, the residual for the Vicon was therefore set to a low angle (SD = 0.1°).

Peach and EmPower angles were plotted against Vicon angle to visually assess error, revealing greater error in EmPower units (Figure 3.3). Effects in Peach and EmPower were therefore analysed separately, and to reduce the time required for convergence of the mixed model (which ran over 8 h when Peach and EmPower were included). Three peach units were excluded from analysis after evidence of baseplate rotation on the pin was observed during analysis (greater residual SD for those units compared to the other units in some stroke-rate bands). Residuals for remaining units showed some minor differences that are not presented in the results section; instead, further analyses were performed in which one residual was specified for these units, representing the population random error; in these analyses the random effect for serial number was converted to a fixed effect to estimate systematic error for specific units. No evidence of baseplate rotation was identified in any EmPower units. Outliers were identified as strokes with a standardized residual greater than 4.5 (Hopkins, Marshall, Batterham, & Hanin, 2009). Occurrence of outliers was infrequent, with approximately 0.1% of strokes identified. Outliers were included in the analysis as such strokes would not be identifiable and therefore not removed when Peach and EmPower are used in the field.

Coker (2010) used standardisation to define the smallest important angle of 0.5° from 0.2× the between-subject differences in mean catch angle of approximately 2.5° in elite rowers. Corresponding thresholds based on standardization (Hopkins et al., 2009) for assessment of mean effects representing systematic error were: <0.5° (trivial), ≥0.5° (small), ≥1.5° (moderate), ≥3.0° (large), ≥5.0° (very large), and ≥10.0° (extremely large). Thresholds for assessment of SD representing random error were half these values (T. B. Smith & Hopkins, 2011): <0.25° (trivial), ≥0.25° (small), ≥0.8° (moderate), ≥1.5° (large), ≥2.5° (very large), and ≥5.0° (extremely large).

Sampling uncertainty in effects and SD is shown as 90% compatibility limits (90%CL), derived by assuming a normal distribution (t for effects, z for SDs squared; 90%CL for SD are shown in approximate ± form). Decisions about magnitudes accounting for the uncertainty were based on one-sided interval hypothesis tests, according to which an hypothesis of a given magnitude (substantial, non-substantial) is rejected if the 90% compatibility interval falls outside that magnitude (Aisbett, Lakens, & Sainani, 2020; Hopkins, 2020). P values for the tests were therefore the areas of the sampling distribution of the effect falling in the hypothesized magnitude, with the distribution centered on the observed effect. Hypotheses of inferiority (substantial negative) and superiority (substantial positive) were rejected if their respective p values ($p_–$ and p_+) were <0.05; rejection of both hypotheses represents a decisively trivial effect in equivalence testing. When only one hypothesis was rejected, the p value for the other hypothesis, when >0.25, was interpreted as the posterior probability of a substantial true magnitude of the effect in a reference-Bayesian analysis with a minimally informative prior (Hopkins, 2019) using the following scale: >0.25, possibly; >0.75, likely; >0.95, very likely; >0.995, most likely (Hopkins et al., 2009); the probability of a trivial true magnitude ($1 – p_– – p_+$) was also interpreted, when >0.25, with the same scale. Probabilities were not interpreted for effects that were unclear (those with inadequate precision at the 90% level, defined by failure to reject both hypotheses, $p_–$>0.05 and p_+>0.05). The hypothesis of non-inferiority (non-substantial-negative) or non-superiority (non-substantial-positive) was rejected if its p value ($p_{N–} = 1 – p_–$ or $p_{N+} = 1 – p_+$) was <0.05, representing a decisively substantial effect in minimal-effects testing: very likely or most likely substantial.

Magnitude of random error in a given angle can also be assessed for its effect on relationships between the angle and performance. The relationships will be presented in a forthcoming study as the linear effect of within-rower stroke-to-stroke changes in the angle on boat velocity. Expressed as a slope, the linear effect would be modified by a factor of $SD^2/(SD^2+e^2)$, where SD is the within-rower stroke-to-stroke standard deviation measured with Vicon and e is the random error in the Peach or EmPower in the angle (Hopkins et al., 2009). The modifying factor was derived using the SD of the participant in the present study.

3.4 Results

Catch, finish, and arc angles as measured by Vicon in each stroke-rate band are presented in Table 3.1. The SD shown represent participant stroke-to-stroke variability, which was ~2.0° for catch, ~1.0° for finish, and ~2.5° for arc angle, depending on the stroke rate. Figure 3.3 illustrates Peach and EmPower catch and finish angles plotted against Vicon catch and finish angles for the same strokes.

Table 3.1 Catch, finish, and arc angles measured with Vicon system at different stroke rates. Data are mean ± SD (°).

Stroke rate	Catch angle	Finish angle	Arc angle
16-28 min^{-1}	-55.2 ± 1.7	33.4 ± 1.0	88.6 ± 1.2
30-36 min^{-1}	-52.5 ± 2.2	32.6 ± 1.0	85.1 ± 2.7
38-44 min^{-1}	-49.4 ± 1.8	31.8 ± 1.0	81.3 ± 2.5
Maximal	-41.9 ± 2.2	30.8 ± 0.8	72.8 ± 2.4

Number of strokes for each stroke-rate band: 16-28 min^{-1}, ~980; 30-36 min^{-1}, ~560; 38-44 min^{-1}, ~560; maximal, ~140.

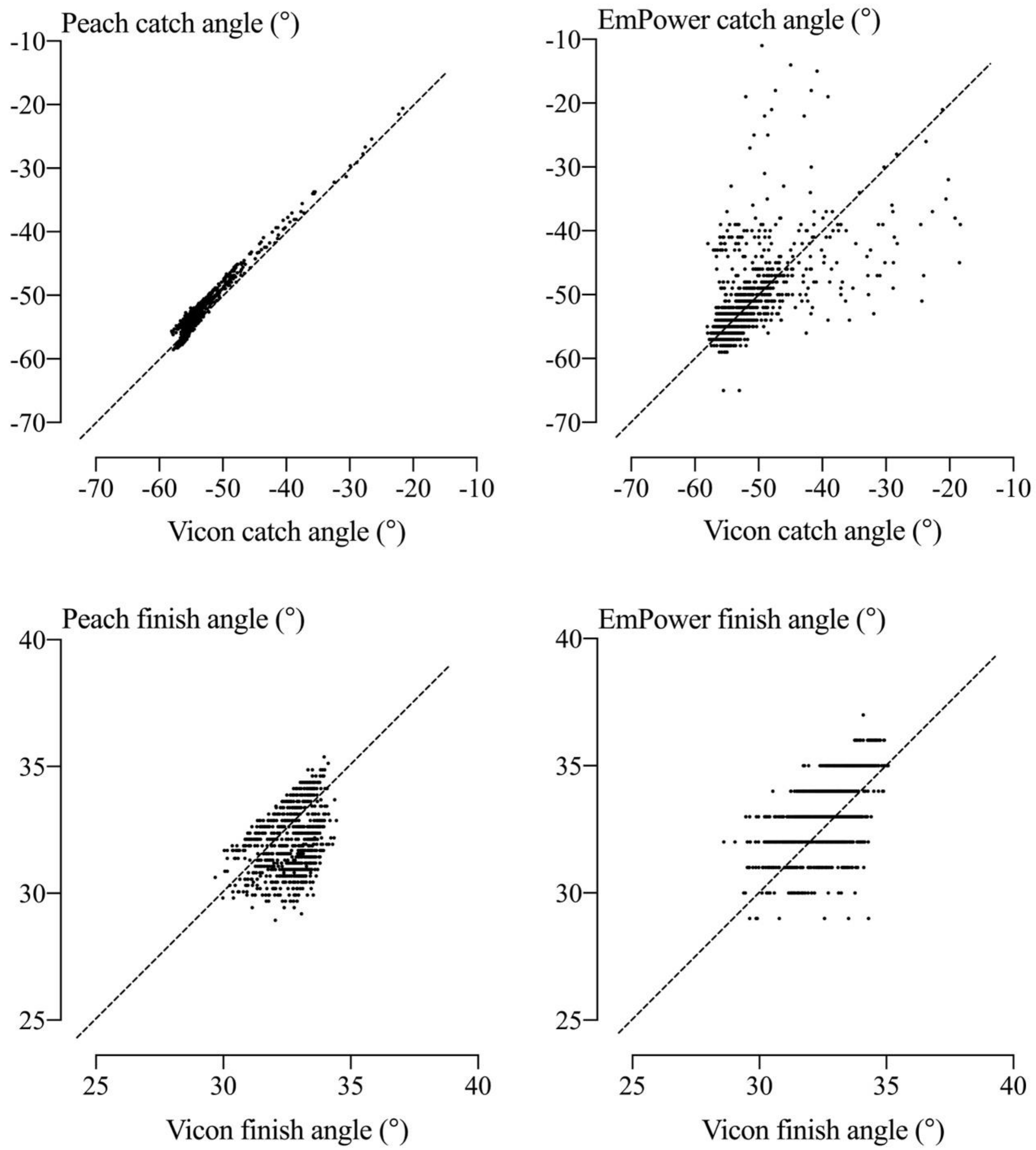

Figure 3.3 EmPower and Peach catch and finish angles plotted against Vicon catch and finish angles. Dashed line indicates perfect agreement between EmPower or Peach and Vicon. Note the change in scale between catch and finish angles.

Systematic error of the population of Peach and EmPower units represented by the mean difference from Vicon is presented for each stroke-rate band and angle in Table 3.2. Systematic error in Peach was small and mostly unclear (the superiority and inferiority hypotheses were not rejected, p_+ and p_- >0.05) for catch angle, mostly trivial but unclear for finish angle, and moderate or small and decisively substantial (rejection of the non-inferiority hypotheses, p_{N-} <0.05) for arc angle. Similar systematic errors were evident in EmPower, with mostly trivial but unclear effects for catch angle, mostly small effects that were possibly substantial (only one of the superiority and inferiority hypotheses was rejected, p_+ or p_- >0.05) in two stroke-rate bands for finish angle, and trivial or small but unclear effects for arc angle.

Table 3.2 Systematic error from Vicon system in the population mean of Peach and EmPower devices for catch, finish, and arc angles at different stroke rates. Data are mean with ±90% compatibility limits (°), with observed magnitudes and p values for inferiority and superiority tests ($p_{–}$/p_{+}).

Stroke rate	Catch angle	Finish angle	Arc angle
Peach			
16-28 min^{-1}	0.9, ±1.9; small 0.9/0.68	-1.0, ±1.4; small* 0.73/0.04	-1.8, ±0.5; moderate*** 0.99/0.003
30-36 min^{-1}	1.1, ±1.8; small 0.06/0.79	-0.4, ±2.3; trivial 0.46/0.19	-1.5, ±0.6; moderate*** 0.98/0.004
38-44 min^{-1}	1.1, ±1.8; small 0.06/0.79	-0.3, ±2.2; trivial 0.41/0.21	-1.4, ±0.5; small*** 0.98/0.004
Maximal	1.3, ±1.2; small** 0.03/0.91	-0.0, ±2.0; trivial 0.28/0.26	-1.3, ±0.5; small*** 0.99/0.002
EmPower			
16-28 min^{-1}	0.7, ±0.6; small* 0.001/0.74	0.4, ±1.1; trivial 0.07/0.43	-0.3, ±1.9; trivial 0.43/0.21
30-36 min^{-1}	0.3, ±1.0; trivial 0.10/0.36	0.5, ±0.4; small* <0.001/0.54	0.4, ±2.0; trivial 0.22/0.45
38-44 min^{-1}	-0.2, ±0.9; trivial 0.26/0.10	0.6, ±0.4; small* <0.001/0.63	0.8, ±2.7; small 0.17/0.60
Maximal	0.4, ±2.1; trivial 0.25/0.46	0.7, ±1.3; small 0.06/0.63	0.5, ±2.2; small 0.21/0.52

Numbers of strokes are approximately half those in Table 3.1.
Scale of magnitudes: <0.5°, trivial; ≥0.5°, small; ≥1.5°, moderate (mod); ≥3.0°, large; ≥5.0°, very large (v.large); ≥10.0°, extremely large (e.large).
Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely, ****most likely.
*** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005 respectively).
Likelihoods are not shown for effects that are unclear at the 90% level (failure to reject any hypotheses: p>0.05).

Differences in systematic error among Peach and EmPower units represented by SD are presented in Table 3.3. These between-unit differences were mostly moderate and unclear for Peach catch and finish angles and were small but only possibly substantial in the two highest stroke-rate bands for arc angle. Between-unit differences in EmPower were small or moderate for catch and finish angles, and decisively substantial in some stroke-rate bands. There were large between-unit differences for arc angle in EmPower, which were likely substantial (only one of the superiority and inferiority hypotheses was rejected, p_+ or p_- >0.05) in one stroke-rate band, but unclear for the others.

Table 3.3 Differences in systematic error among Peach and EmPower units for catch, finish, and arc angles at different stroke rates. Data are SD with ±90% compatibility limits (°), with observed magnitudes and p values for inferiority and superiority tests ($p_–/p_+$).

Stroke rate	Catch angle	Finish angle	Arc angle
Peach			
16-28 min^{-1}	1.2, ±1.4; moderate 0.14/0.84	1.2, ±1.1; moderate 0.07/0.92	0.3, ±0.4; small 0.05/0.64
30-36 min^{-1}	1.1, ±1.3; moderate 0.14/0.83	1.4, ±1.7; moderate 0.15/0.83	0.3, ±0.4; small 0.06/0.67
38-44 min^{-1}	1.1, ±1.3; moderate 0.15/0.83	1.3, ±1.6; moderate 0.15/0.83	0.3, ±0.4; small* 0.04/0.60
Maximal	0.7, ±0.9; small 0.14/0.80	1.2, ±1.4; moderate 0.15/0.83	0.4, ±0.4; small* 0.04/0.71
EmPower			
16-28 min^{-1}	0.7, ±0.2; small**** <0.001/0.999	0.9, ±1.0; moderate 0.09/0.88	1.9, ±1.6; large 0.06/0.93
30-36 min^{-1}	1.1, ±0.4; moderate*** 0.002/0.99	0.5, ±0.1; small*** <0.001/0.99	2.0, ±1.4; large** 0.04/0.95
38-44 min^{-1}	0.8, ±0.7; moderate 0.06/0.90	0.4, ±0.1; small*** <0.001/0.99	2.1, ±2.5; large 0.15/0.84
Maximal	0.0[a]	1.1, ±1.2; moderate 0.10/0.87	0.0[a]

Numbers of strokes are approximately half those in Table 3.1.

[a]Indicates negative estimate probably due to sampling variation, so estimated as 0 and therefore no CL; true value likely similar to other stroke-rate bands.

Scale of magnitudes: <0.25°, trivial; ≥0.25°, small; ≥0.75°, moderate (mod); ≥1.5°, large; ≥2.5°, very large (v.large); ≥5.0°, extremely large (e.large).

Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely, ****most likely.

*** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005 respectively).

Likelihoods are not shown for effects that are unclear at the 90% level (failure to reject any hypotheses: p>0.05).

In the analyses with serial number as a fixed effect (not shown in Tables), one of the three Peach units had decisively trivial systematic error (rejection of both the superiority and inferiority hypotheses, p_+ and $p_– <0.05$), except at the highest stroke rate, where there was small and decisively substantial error. The other two units showed systematic error, ranging from small to moderate and likely substantial to decisively substantial. The same analyses for the four EmPower units showed either substantial or, at the higher stroke rates, unclear error for each unit.

Random errors were first analysed by allowing each unit to have its own random error (the residual). Given the uncertainties in the estimates for each unit (90% compatibility limits ~×/÷1.10 for submaximal stroke-rate bands, ~×/÷1.30 for the maximal stroke-rate band), the observed differences in random error between the four EmPower units for catch, finish, and arc angles were consistent with differences due entirely to sampling variation. However, one unit showed an obviously larger error than the other units for finish angle in the 30-36 and 40-44 stroke-rate bands. The three Peach units showed differences in random errors for catch, finish, and arc angles that were sometimes outside the limits of uncertainty related to sampling variation (same factor uncertainties as for EmPower), although the errors were of the order of 0.1-0.8°. The average random error across units was therefore estimated from the analyses that allowed for a single population random error and are presented in Table 3.4. For Peach, random errors were mostly small and decisively substantial for catch, finish, and arc angles, while finish angle in the two highest stroke-rate bands had errors that were decisively trivial, and possibly trivial (rejection of only the inferiority hypothesis, $p_– <0.05$). For EmPower, mostly extremely large and decisively substantial errors were observed for catch and arc angles, and mostly moderate and decisively substantial errors were observed for finish angle. Larger random errors also appeared to be associated with higher stroke rates in catch, finish, and arc angles in EmPower. Vicon random errors were negligible (<0.1°). The random errors combined with the participant's stroke-to-stroke variability from Vicon (Table 3.1) would result in modification of linear effects of stroke angle on performance by factors of 0.97, 0.92 and 0.97 for Peach catch, finish and arc angles, respectively; the corresponding factors for EmPower would be 0.14, 0.10 and 0.11. The factors for catch and finish angles for elite rowers would be 0.82 and 0.92, based on the stroke-to-stroke variability in elite scullers (Coker, 2010).

Table 3.4 Population random error in Peach and EmPower devices for catch, finish, and arc angles at different stroke rates. Data are SD with ×/÷90% compatibility limits (°), with observed magnitudes and p values for inferiority and superiority tests ($p_{–}/p_{+}$).

Stroke rate	Catch angle	Finish angle	Arc angle
Peach			
16-28 min^{-1}	0.4, ×/÷1.06; small**** <0.001/>0.999	0.4, ×/÷1.06; small**** <0.001/>0.999	0.5, ×/÷1.06; small**** <0.001/>0.999
30-36 min^{-1}	0.4, ×/÷1.08; small**** <0.001/>0.999	0.4, ×/÷1.08; small**** <0.001/>0.999	0.5, ×/÷1.08; small**** <0.001/>0.999
38-44 min^{-1}	0.3, ×/÷1.10; small**** <0.001/>0.999	0.2, ×/÷1.10; trivial^{000} <0.001/0.03	0.4, ×/÷1.10; small**** <0.001/>0.999
Maximal	0.5, ×/÷1.19; small**** <0.001/>0.999	0.2, ×/÷1.19; trivial^{0} <0.001/0.42	0.4, ×/÷1.19; small**** <0.001/>0.999
EmPower			
16-28 min^{-1}	3.2, ×/÷ 1.05; large**** <0.001/>0.999	0.8, ×/÷1.05; moderate**** <0.001/>0.999	3.7, ×/÷1.05; v.large**** <0.001/>0.999
30-36 min^{-1}	5.1, ×/÷1.07; e.large**** <0.001/>0.999	1.4, ×/÷1.03; moderate**** <0.001/>0.999	7.0, ×/÷1.07; e.large**** <0.001/>0.999
38-44 min^{-1}	6.0, ×/÷1.08; e.large**** <0.001/>0.999	3.9, ×/÷1.08; v.large**** <0.001/>0.999	8.5, ×/÷1.08; e.large**** <0.001/>0.999
Maximal	11.6, ×/÷1.16; e.large**** <0.001/>0.999	0.8, ×/÷1.16; moderate**** <0.001/>0.999	11.6, ×/÷1.16; e.large**** <0.001/>0.999

Numbers of strokes are approximately half those in Table 3.1.

Scale of magnitudes: <0.25°, trivial; ≥0.25°, small; ≥0.75°, moderate (mod); ≥1.5°, large; ≥2.5°, very large (v.large); ≥5.0°, extremely large (e.large).

Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely, ****most likely.

*** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005 respectively).

Reference-Bayesian likelihoods of trivial change: ^{0}possibly; ^{00}likely; ^{000}very likely, ^{0000}most likely.

^{000} indicates rejection of the superiority and inferiority hypotheses (p_{N-} and p_{N+} <0.05)

3.5 Discussion

This is the first study to assess the concurrent validity of Peach PowerLine and Nielsen-Kellerman EmPower rowing instrumentation systems through an on-water rowing-specific range of oar angles and stroke rates (Feigean, R'Kiouak, Bootsma, & Bourbousson, 2017; Smith & Draper, 2006). The findings in this study show Peach to have reasonable concurrent validity for catch, finish, and arc angle detection compared to the Vicon motion analysis system; however, validity was not adequate for EmPower due to the magnitudes of random error for this device.

When assessing and advising rower attainment of specified catch, finish, or arc angle targets, coaches and sport scientists should note the systematic errors reported in Table 3.2. The current results indicate systematic errors of approximately 1° for catch angle and 1.5° for arc angle in Peach, and <1° for finish angle in Peach, and catch, finish, and arc angles in EmPower. These errors are generally larger than the ~0.6° reported for static angle assessment of Peach units (Coker et al., 2009), likely due to the dynamic testing of devices in this study. Differences in systematic error between the three Peach units and four EmPower units, although mostly unclear for Peach, are consistent with substantial between-unit differences. The reasonably small number of units assessed contributed to the uncertainty. Nevertheless, the between-unit differences for Peach and EmPower should be considered when conducting repeated oar angle analyses or when comparing rowers: it is recommended that the same unit be used to reduce errors from between-unit differences.

Systematic errors were generally similar across stroke-rate bands for the angles assessed. However, substantial errors were observed for arc angle in Peach, and appear to be due mainly to errors arising for catch angle. Furthermore, the systematic error estimates for arc angle are consistent with the simple addition of those for catch and finish angles (considering the uncertainties in the errors), indicating that errors for catch and finish angles are not a result of device set-up or calibration errors, as any calibration inaccuracies would disappear when deriving the arc angle. Although systematic errors do not appear to be related to device calibration in the current study, between-assessment differences may arise in the field if calibration of device angle is not performed with care.

Random error for Vicon was negligible. Random error for Peach was acceptable for single-stroke angle assessment, and the error would be negligible (<0.25°) if several strokes were averaged, because the error in the mean of n strokes is $e/\sqrt{n}$, where e is the error in a single stroke. Random error in Peach would also produce negligible attenuation of relationships between oar angles and rowing performance for the participant in the present study, and there would be little more attenuation for elite rowers. Small differences between the random errors were observed in some Peach units and may have been a result of undetected baseplate rotation. The unusual set-up on the Swingulator may have contributed to baseplate rotation. In the experience of one of the authors, baseplate rotation is not an issue when the units are used on water, but the baseplate position should be checked carefully following on-water use, as baseplate rotation may contribute errors of ~0.5°.

In contrast to Peach, EmPower had unacceptable errors for stroke-to-stroke angle assessment, which would practically eliminate relationships between oar angles and rowing performance. The magnitude of random error found for EmPower is illustrated in the spread of data in Figure 3.3. Caution is therefore advised when using EmPower for on-water angle measurement, especially at higher stroke rates, where errors appear to increase. Assessment of mean angle over a considerable number of strokes is recommended; using the above formula, the strokes required ranges from ~30 to ~1000, for assessments at race rates (30-44 min^{-1}), depending on angle and rate.

3.5.1 Practical Applications

- Peach can be used with confidence for measures of stroke-to-stroke catch, finish, and arc angles, and for the assessment of relationships between gate angle and rowing performance, given its ~0.4° random error estimates.
- EmPower is best used to assess mean catch, finish, and arc angles rather than stroke-to-stroke measures, owing to its high random error estimates (0.8 to 11.6°).
- Use of the same unit is recommended for repeated measurements of catch, finish, or arc angles or the comparison of measures between rowers, due to the ~0.3 to 1° (Peach) and ~1 to 2° (EmPower) between-unit differences observed in systematic error.

3.6 Conclusion

The findings of the current study demonstrate acceptable concurrent stroke-to-stroke validity of Peach with Vicon as the criterion, for catch, finish, and arc angles across all stroke-rate bands. Validity for EmPower was unacceptable, owing to its random-error magnitudes; as such, analysis of angles over a large number of strokes is recommended when using EmPower. Some substantial between-unit differences in systematic error were observed in both Peach and EmPower, therefore using the same unit is recommended for repeated assessments.

Chapter Four: Concurrent validity of Power from Three On-water Rowing Instrumentation Systems and a Concept2 Ergometer

4.1 Abstract

Purpose: Instrumentation systems are increasingly used in rowing to measure training intensity and performance but have not been validated for measures of power. In this study, the concurrent validity of Peach PowerLine (six units), Neilsen-Kellerman EmPower (five units), Weba OarPowerMeter (three units), Concept2 model D ergometer (one unit), and a custom-built reference instrumentation system (Reference System; 1 unit) were investigated. **Methods:** Eight female and seven male rowers (age, 21 ± 2.5 y; rowing experience, 7.1 ± 2.6 y, mean ± standard deviation [SD]) performed a 30-s maximal test and a 7x4-min incremental test once per week for 5 wk. Power per stroke was extracted concurrently from the Reference System (via chain force and velocity), the Concept2 itself, Weba (oarshaft-based), and either Peach or EmPower (gate-based). Differences from the Reference System in the mean (representing potential error) and the stroke-to-stroke variability (represented by its SD) of power per stroke for each stage and device, and between-unit differences, were estimated using general linear mixed modelling and interpreted using rejection of non-substantial and substantial hypotheses. **Results:** Potential error in mean power was decisively substantial for all devices (Concept2, -11 to -15%; Peach, -7.9 to -17%; EmPower, -32 to -48%; Weba, -7.9 to -16%). Between-unit differences (as SD) in mean power lacked statistical precision but were substantial and consistent across stages (Peach, ~5%; EmPower, ~7%; Weba, ~2%). Most differences from the Reference System in stroke-to-stroke variability of power were possibly or likely trivial or small for Peach (-3.0 to -16%), and likely or decisively substantial for EmPower (9.7 to 57%), and mostly decisively substantial for Weba (61 to 139%) and the Concept2 (-28 to 177%). **Conclusion:** Potential negative error in mean power was evident for all devices and units, particularly EmPower. Stroke-to-stroke variation in power showed a lack of measurement sensitivity (apparent smoothing) that was minor for Peach but larger for the Concept2, whereas EmPower and Weba added random error. Peach is therefore recommended for measurement of mean and stroke power.

4.2 Introduction

Rowing instrumentation systems provide a comprehensive measure of performance given their ability to assess both technical and physical components of rowing performance and enable instantaneous quantitative feedback to the rower (Lintmeijer, Onneweer, et al., 2019). Instantaneous feedback of power output has been shown to improve training intensity adherence by 65% in rowers compared to boat velocity, stroke rate and coach feedback alone (Lintmeijer, van Soest, et al., 2019). Furthermore, on-water power measurement in rowing has potential widespread value in the quantification of external training load, analysis of race demands, and performance monitoring via power-based benchmarks, all of which have been achieved with instrumentation systems in cycling (Nimmerichter, Eston, Bachl, & Williams, 2011; Sanders & Heijboer, 2019; Schumacher & Mueller, 2002a). However, before rowing instrumentation systems can be used with some certainty, their validity must first be established. Knowledge of the systematic error and random error associated with measures of power from rowing instrumentation devices will inform the interpretation of a meaningful change or difference in power for the given device.

Different types of rowing instrumentation systems exist and can be located at the gate or on the oar shaft. Instrumentation systems located on the gate measure forces occurring at the pin resulting from the transfer of force applied at the handle to the oar blade. Oar shaft-based instrumentation systems are positioned on the oar's inboard (the section of oar shaft between the handle and the point of the oar's rotation at the gate) and calculate the moment of force applied to the handle from the deflection of the oar throughout the stroke (Kleshnev, 2010b).

The validity of power measurement off-water has been investigated using mechanical sensors attached to Concept2 ergometer models A and D, with negative systematic error estimates of 5 to 8 % reported (Boyas et al., 2006; Lormes et al., 1993). However, the validity of power from on-water instrumentation systems is yet to be established. Research investigating the validity of rowing instrumentation systems has focused on gate-based Peach PowerLine devices (Peach Innovations, Cambridge, UK), encompassing static (Laschowski & Nolte, 2016) or dynamic linear force application and static angle assessment (Coker et al., 2009). Eight Peach sculling units had reasonable concurrent validity for measures of force up to 555 N and angle between -80° to 60°, with standard error of the estimate (SEE) values of 7.16 ± 2.56 N for force and 0.9 ± 0.9° SEE for angle (Coker et al., 2009). Very large correlations between applied and measured forces of up to 432 N were also reported for eight sculling (r = 0.985) and nine sweep (r = 0.986) Peach units, although a negative error of 2% was observed for Peach (Laschowski & Nolte, 2016). However, the testing methods of these studies do not reflect a rowing-specific pattern of force application or gate angular rotation. Force at the gate throughout a rowing stroke increases to a peak mid-drive with a subsequent decrease from mid-drive to the end of the drive phase, and therefore do not reflect the static force application used in previous validity studies. Similarly, the measurement of catch and finish gate angles during a rowing stroke occur during rotation at each end of the stroke when the oar changes direction, which is not reflected in the static measurement of gate angle used previously. As such, the applicability of results from previous validity studies to the measurement of power on-water is unknown. Furthermore, the validity of power measures has not been investigated in Peach or other commercially available rowing instrumentation systems such as the Nielsen-Kellerman EmPower (Kleshnev, 2017) and Weba Sport OarPowerMeter in peer-reviewed research. Therefore, the aim of this study was to assess the concurrent validity of power measures from Peach PowerLine, Nielsen-Kellerman EmPower, Weba Sport OarPowerMeter sweep rowing instrumentation systems, and a Concept2 ergometer with an instrumented Swingulator Team Sweep system through a dynamic, on-water rowing specific range of oar angles and force applications.

4.3 Methods

4.3.1 Participants

Eight female (age 21.6 ± 3.1 y; height 175.9 ± 4.1 cm; body mass 76.7 ± 5.4 kg, mean ± standard deviation [SD]) and seven male (age 20.9 ± 2.0 y; height 189.7 ± 8.4 cm; body mass 86.2 ± 11.0 kg) trained rowers with 7.1 ± 2.6 y experience at a national level who were actively participating in the sport at the time of the study and had competed in the previous rowing season volunteered for this study. Six of the participants (5 females, 1 male) had previously represented Australia at International regattas. Participants provided informed consent prior to commencement of the study. The study was approved by the University Human Research Ethics Committee.

4.3.2 Equipment

All rowing was performed on an instrumented Swingulator team sweep trainer (Rowing Innovations Inc., Williston, VT) with a Concept2 ergometer (Model D with PM5 monitor, Concept2 Inc., Morrisville, VT) attachment. The Swingulator was used as it enables the simulation of on-water sweep rowing in a controlled land-based environment, where power could be recorded from the Reference System, Weba, Concept2, and Peach or EmPower simultaneously. The Swingulator also allowed instrumentation with mechanical sensors (as described in the next paragraph) to provide a comparative measure of power for the assessment of concurrent validity. When using the Swingulator the rower holds the handle of an oar with a shortened outboard which sits in an gate, the end of the oar's outboard (between the oar's collar and blade-end) connects to a cable which passes through four pulleys before connecting to the chain of the Concept2, which provides resistance during the drive phase of the rowing stroke (Figure 4.1). Oar inboard (between the oar's handle and collar) and total oar lengths were set to 114.5 and 177 cm respectively, with span (distance between the pin and the center of the hull) set to 84.3 cm.

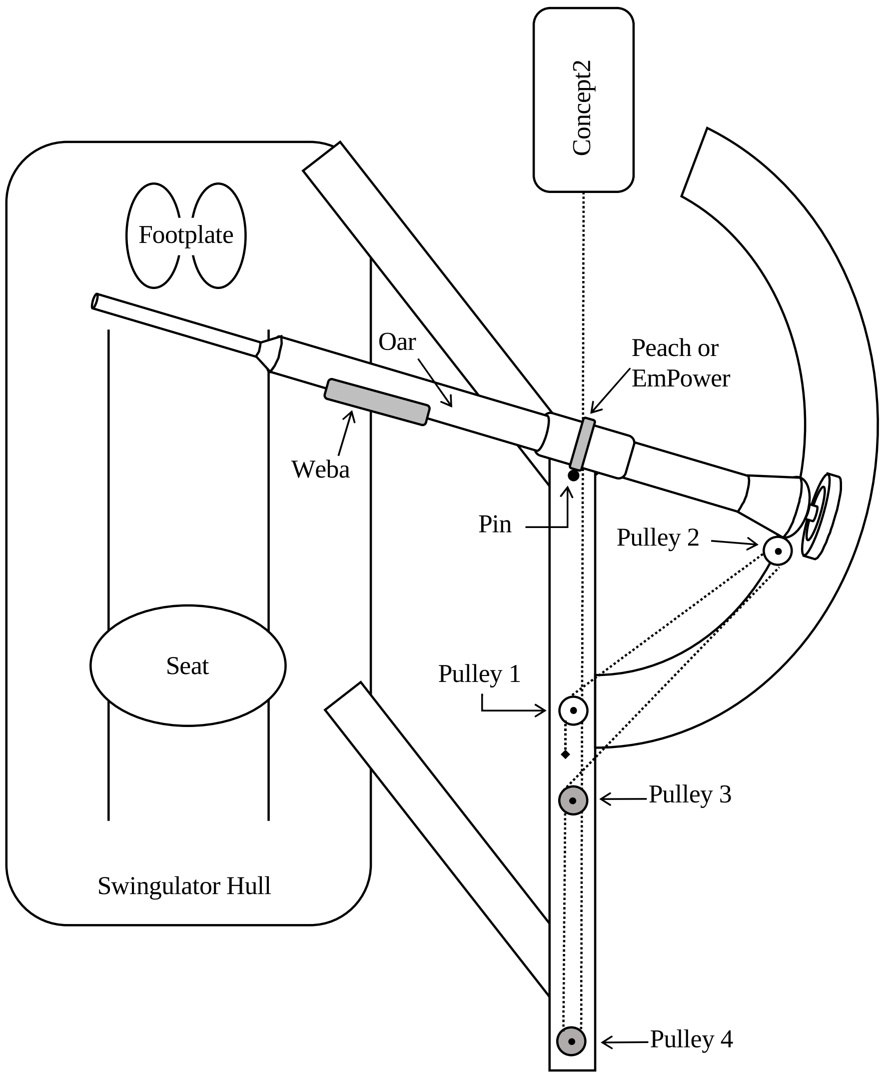

Figure 4.1. Birds-eye view diagram (not drawn to scale) of Swingulator system illustrating location of devices. Pin, point of oar rotation. Pulley 2 is attached to the oar, Pulleys 3 and 4 are located on the underside of the Swingulator framing. Dashed line represents the Concept2 chain and Swingulator cord which passes under the framing after Pulley 2. The black diamond near Pulley 1 indicates the anchor point of the Swingulator cord.

The Concept2 drag factor was set to 80 units for females and 100 units for males, which were lowered by 30 units from typical settings to account for the greater resistance of the Swingulator-Concept2 system. Mechanical sensors (hereafter referred to as the Reference System) were attached to the Swingulator, similar to that used previously on Concept2 ergometers (Boyas et al., 2006; Macfarlane, Edmond, & Walmsley, 1997b), and included a quadrature optical encoder (HEDS-5500 Optical Encoder) coupled inline to the Concept2's chain, allowing finite linear displacement to be measured with regard to a fixed reference mark. A force transducer (DACELL UMMA-K200) was housed in a custom attachment (Küsel Dësign, Melbourne, Australia) at Pulley 4 on the Swingulator assembly (Figure 4.2), enabling the measurement of force applied through the Swingulator cord when a participant pulled on the oar handle. Static testing of the force transducer without attachment to the Swingulator against a known mass between 0.2 to 85.8 kg was undertaken to verify the linearity characteristics and the voltage-force-mass relationship, which had an R^2 value of 1.00. The quadrature optical encoder was assessed in pilot testing using a Vicon analysis system (T-40 series, Vicon Nexus v2.7, Oxford, UK) with a 14 mm diameter reflective marker attached to the Concept2 chain. An R^2 value of 0.99 was found between the quadrature optical encoder and the Vicon analysis system for the measurement of Concept2 chain displacement.

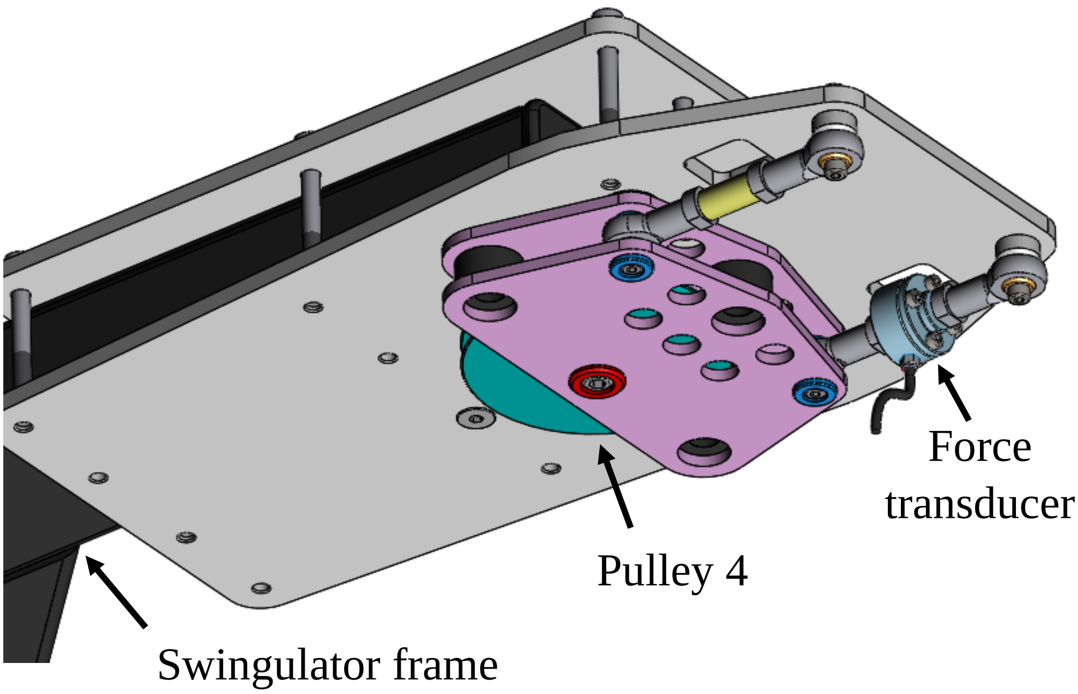

Figure 4.2. Custom Swingulator attachment with force transducer at Pulley 4.

Calibration of the Reference System's force and displacement measurement on the Swingulator was performed every seven days throughout the study. For force calibration, the oar handle was locked perpendicular to the Swingulator's hull and loaded with a known mass (1000.4 N; 101.98 kg). Calibration of the quadrature optical encoder was achieved by movement of the chain through its full range on the Swingulator (~2030 mm). Although calibration of the Reference System could not be performed prior to each testing session due to the timeframes involved, the analysis allowed the error introduced between sessions that was associated with the Reference System to be partitioned out from that introduced by the other devices, and is reported in the results section.

The concurrent validity of power from Peach PowerLine (Peach Innovations, Cambridge, UK), EmPower (Nielsen-Kellermen, Boothwyn, PA), Weba (OarPowerMeter, Weba Sport, Wien, Austria) sweep instrumentation devices and the Concept2 ergometer were tested. Differences in concurrent validity between different units for each device was also assessed through testing of six Peach units, five EmPower units, and three Weba units. Peach and EmPower units were attached to the Swingulator's pin, replacing the gate. Peach and EmPower baseplates were attached to the pin at 90° to the Swingulator's hull (as per manufacturer's instructions) using a straight edge and goniometer (EZ Read, Jamar, Performance Health, IL). Weba devices were placed facing the participant on the inboard of the oar shaft, as per manufacturer's instructions.

Calibration procedures for Peach, EmPower and Weba devices were performed in accordance with manufacturer instructions immediately prior to each testing session. Calibration of the gate angle for Peach and EmPower devices was achieved using a goniometer and straight edge to set the unit's angle as 0° when the gate's flat edge was 90° to the Swingulator's hull. An additional angle calibration routine was performed for EmPower units using the calibration tool supplied by the manufacturer, successful calibration for this additional process was determined by the unit itself. Force for Peach and EmPower devices was calibrated via zeroing the unit's force measure with the oar removed. Calibration of Weba devices was achieved via the hanging of a known mass (198.3 N; 20.22 kg) ~10 cm from the handle tip with the oar's outboard held in a horizontal position on a bench with the Weba unit facing downwards.

4.3.3 Study design

The study was conducted in a temperature-controlled environment (21.1 ± 1.0 °C; 48.6 ± 9.9% RH). Participants performed five testing sessions on the Swingulator team sweep trainer separated by 7.0 ± 2.0 days, including one initial familiarisation session. A schematic of the testing session procedures is illustrated in Figure 4.3. Testing sessions included a 10 min warm-up of low-intensity rowing interspersed with three maximal 10-stroke efforts, then a maximal 30-s rowing test at a self-selected stroke rate. Following a subsequent 10 min rest period participants undertook a 7 x 4-min incremental test at self-selected stroke rates, including a final maximal 4-min stage (Tanner & Gore, 2013). A 60 s recovery period was performed between each stage of the incremental test. Participants were instructed to maintain a prescribed power for Stages 1-6 of the incremental test, which were individualised based on the participants most recent 2000-m ergometer test (Tanner & Gore, 2013), and adjusted to account for the perceived resistance of the Swingulator in comparison to rowing on a standard Concept2 ergometer. The familiarisation session further guided the prescription of prescribed power for Stages 1-6, which remaining constant across the final four testing sessions. Participants were instructed to row full-length strokes for the 30-s test and throughout the 7 x 4-min test. The 30-s maximal and 7 x 4-min incremental tests were selected for the assessment of concurrent validity as they are performed as part the participants' regular rowing testing and were therefore familiar to participants, and provided measures of power across intensities ranging from very low to maximal.

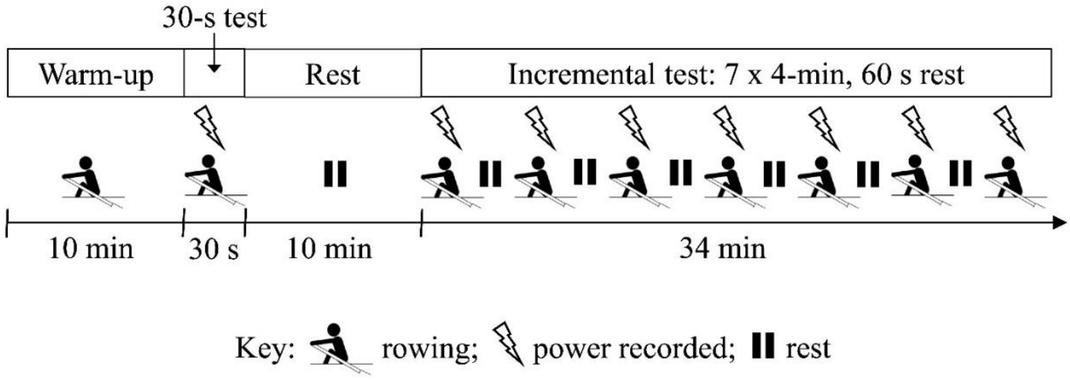

Figure 4.3. Schematic of testing session protocol showing periods of rowing (rower icon), rest (pause icon), and when power was recorded from the five devices (lightning icon). Participants performed the same protocol in each of the five testing sessions, which were separated by 7 days.

The Reference System, Concept2, and Weba were tested concurrently for all testing sessions. The use of Peach or EmPower was alternated per testing session, with each participant performing either two or three testing sessions with each device. The testing order of Weba, Peach and EmPower units was randomised. Peach units were tested in a total of 37 testing sessions, including 20 sessions on bow side and 17 sessions on stroke side, with individual units assessed in 2 to 8 sessions each. EmPower units were tested in a total of 38 testing sessions, including 20 sessions on bow side and 18 sessions on stroke side, with individual units assessed in 4 to 9 sessions each. Weba units were tested in a total of 75 testing sessions, including 40 sessions on bow side and 35 sessions on stroke side, with individual units assessed in 23 to 27 sessions each.

4.3.4 Data analysis

Power per stroke was recorded for Peach and EmPower by their respective head units and exported to a comma-separated values (CSV) file. Power per stroke for Weba was recorded on a Lenovo Tab 4 8 tablet (Lenovo Group Ltd, Beijing), data could not be exported from the tablet so the tablet's screen was recorded and power per stroke manually entered into Microsoft Excel with the manually entered data checked against the recording for input errors. Power per stroke was recorded from the Concept2 using the app PainSled (version 1.1.0, Charlotte Intellectual Properties, LLC, Charlotte, NC) and exported to CSV files.

Chain displacement and force from the Reference System was recorded at 271.7 Hz and filtered in MATLAB (R2019b, The MathWorks, Inc., Natick, MA) using a low-pass fourth order Butterworth filter with cut-off frequencies of 6 and 13 Hz for displacement and force data respectively. The choice of cut-off frequencies were informed by residual analysis (Winter, 1990) and supported by visual inspection of raw and smoothed curves.

The corresponding gate angle for a given chain position was calculated using chain position and gate angle data collected by the Vicon motion analysis system in previous testing of the Swingulator-Concept2 system. Gate angle was plotted over chain position during the drive phase of the stroke (between the maximal negative oar angle and the subsequent maximal positive oar angle per stroke), and fitted with a second order polynomial trendline that had an R-squared (R^2) value of 1.00 (Figure 4.4, A) to derive *a*, *b*, and *c*, in Equation 1:

$$P_C = P_M - \left(\frac{b + \left(\sqrt{b^2 - 4 \cdot a \cdot (c - \theta)} \right)}{2 \cdot a} + P_M \right) \quad (1)$$

Where P_C is the corrected chain position, P_M is the measured chain position, b is 49.81, a is 7.63, c is -51.21, and θ is the initial gate angle at rest.

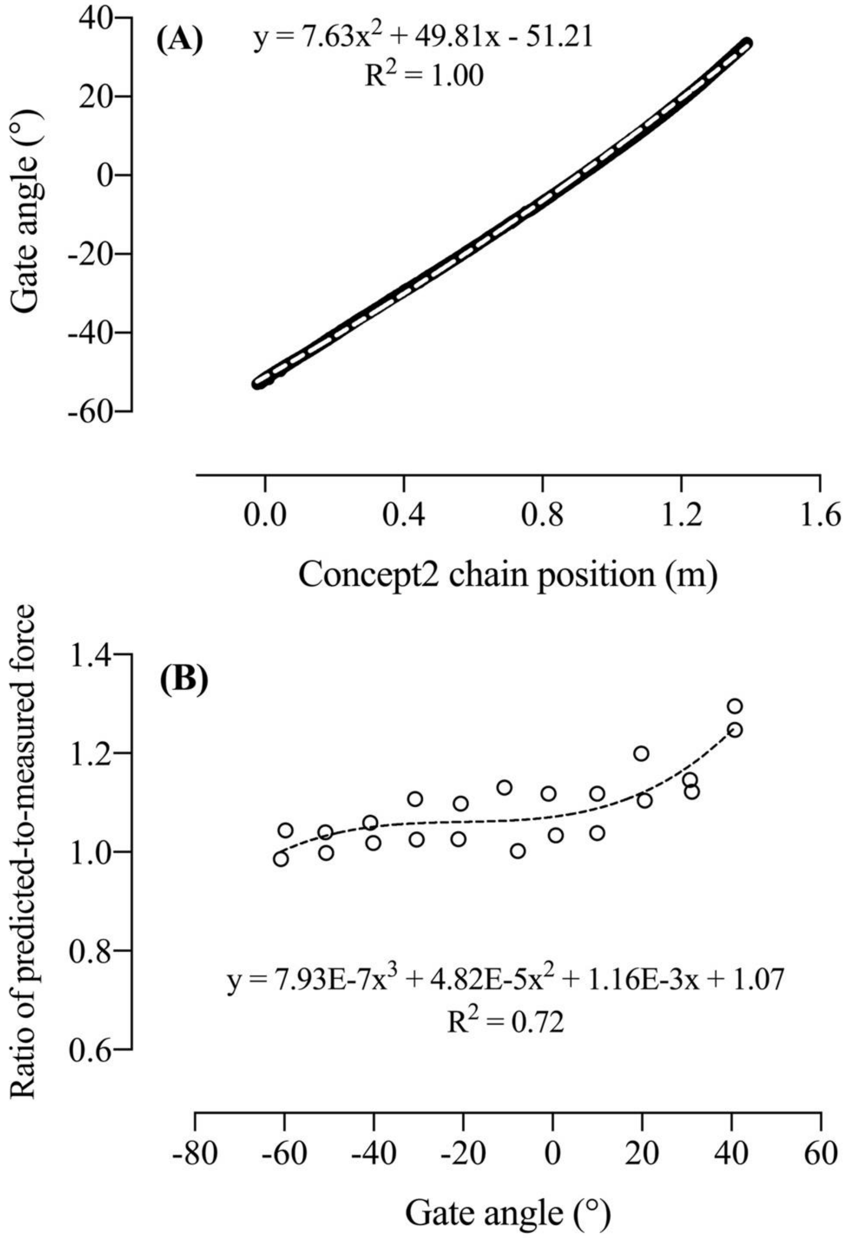

Figure 4.4. Gate angle plotted against Concept2 chain position used to derive *a*, *b*, and *c* in Equation 1 (A); and the ratio of predicted-to-measured force plotted against gate angle used to derive *d*, *e*, *f*, and *g* in Equation 4 (B). Dashed lines represent the fitted trendlines.

The calculated gate angle (θ_C) was then derived by:

$$\theta_C = a \cdot {P_C}^2 + b \cdot P_C - c \tag{2}$$

Due to the geometry of the Swingulator system, force measured at Pulley 4 was corrected relative to the calculated oar angle. A static force of 198.4 N was applied to the oar handle at 11 gate angles ranging between 40.75° to -60.75° on each of bow and stroke sides. First force was predicted (F_P) using Equation 3:

$$F_P = \frac{0.5 \cdot (i/o) \cdot F_A}{cos \cdot (90 - (\sigma + \phi)/2)} \quad (3)$$

Where i was the distance between the pin and the point of force application at the oar handle (1031 mm), o was the distance between the pin and the point on the oar that aligned with the center of Pulley 2 (599 mm), F_A was the force applied to the oar's handle (198.4 N), σ is the angle between the oar shaft and the Swingulator cord on the inner (Figure 4.5) side of Pulley 2, and ϕ is the angle between the oar shaft and the Swingulator cord on the outer side of Pulley 2.

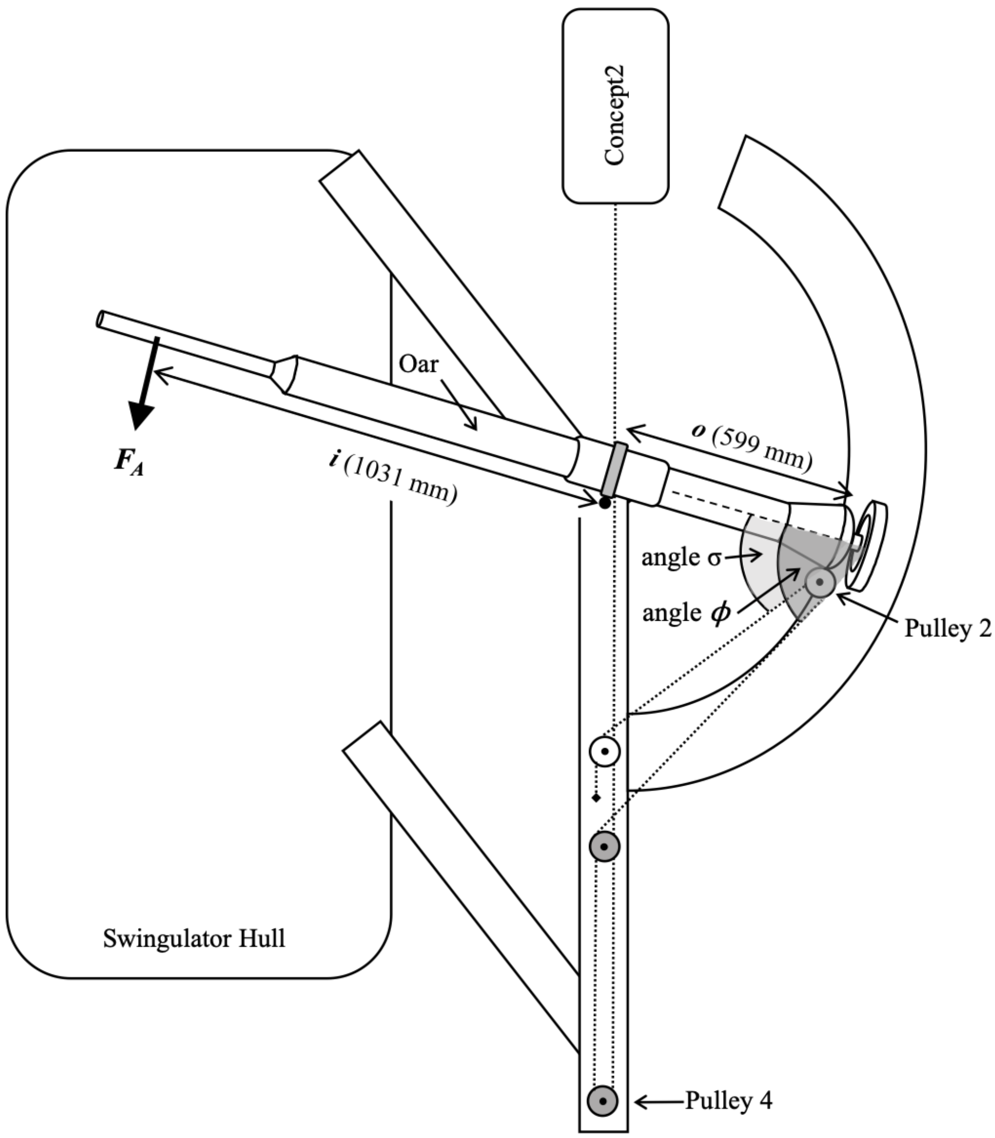

Figure 4.5. Free body diagram of Swingulator-system illustrating the location of the applied force (F_A), distance i, distance o, angle σ, and angle ϕ in Equation 3.

The ratio of predicted-to-measured force was then calculated, plotted against gate angle, and fitted with a third order polynomial trendline that had an R^2 value of 0.72 (Figure 4.4, B) to derive *d*, *e*, *f*, and *g* in Equation 4 for corrected force (F_C):

$$F_C = F_A \times (d \cdot \theta_C{}^3 + e \cdot \theta_C{}^2 + f \cdot \theta_C + g) \quad (4)$$

Where θ_C is the calculated gate angle from Equation 2, *d* is 7.93E-7, *e* is 4.82E-5, *f* is 1.16E-3, and *g* is 1.07.

Instantaneous work (W_i) was then calculated from P_C and F_C for each sample:

$$W_i = \left(\frac{F_{C1}+F_{C2}}{2}\right) \times (P_{C2} - P_{C1}) \quad (5)$$

Where F_{C1} and P_{C1} indicate the previous data point and F_{C2} and P_{C2} indicate the current data point.

Average power per stroke was calculated using Visual 3D (version 6.3, C-motion, Inc. Germantown, USA) from stroke work over stroke time. Stroke time was calculated as the number of samples between consecutive finish positions (the maximum P_C per stroke) multiplied by 0.00368 s (corresponding to the sample rate of 271.7 Hz). Stroke work was calculated as the integral of W_i over the drive phase (from the catch to finish position of the current stroke). Average power per stroke was then calculated as stroke work divided by stroke time and exported from Visual 3D into Microsoft Excel where it was aligned by stroke number with power from Peach or EmPower, Weba, and the Concept2 for each stage.

The first and last two strokes per stage were excluded from analyses from each device to eliminate some inconsistencies between the devices at the onset and termination of rowing. Outliers defined as strokes where power was greater than seven SD from the stage mean power for that device were also excluded; 24 such outliers were identified, but only for Weba units. The magnitude of seven SD was chosen based on time series graphs and represented visually obvious outliers that might prompt the practitioner to disregard the data or repeat the test. This value was chosen as a reasonable compromise between removing data that clearly should be excluded, but not removing data that would not have been visually obvious to practitioners when using devices in the field. Occasionally, errors relating to the recording of devices (both human and device errors) resulted in missing strokes or whole stages for certain device units. Stages where a device had more than five missing strokes were excluded from the analyses for that device. A total of 14 stages were missing or excluded for the Reference System, which were also excluded for the other devices. The number of additional stages missing data or excluded due to missing strokes were three for Peach, one for EmPower, six for Weba, and 32 for the Concept2 (of which the stages excluded due to missing data were split between the 30-s test and Stage 7 and were related to not all strokes being recorded successfully by the PainSled app). After the exclusion of stages with missing data, the mean percentage of strokes missing from analyses (including those excluded as outliers) in each stage were: ≤0.1 % for the Reference System and EmPower; ≤0.2 % for Peach; ≤0.4 % for Weba Stages 1-7, but 2.2 % for the 30-s test; and ≤0.5 % for the Concept2 Stages 1-7, but 6.5 % for the 30-s test. Following the exclusion of these strokes and stages, additional outliers were identified as stages with a standardised residual greater than 4 after running the model (Hopkins et al., 2009). Two Weba stages were identified as outliers from the analysis of mean power, and eight stages (one for the Concept2, five for EmPower, and two for Weba) were identified as outliers from the analysis of the SD of power. All stages identified as outliers were included in the analyses as such data would not be identifiable and therefore not removed when devices are used in the field.

4.3.5 Statistical analysis

Although the data consisted of individual values of mean power for each stroke from each of the five devices, the values for EmPower, Weba, and the Concept2 could not be aligned reliably with those of the Reference System, as can be seen in an example of the data from one stage in Figure 4.6. A repeated-measures analysis of the individual stroke values was therefore not possible. Instead, the mean power for the 30-s stage and for each stage of the incremental test was analysed with a mixed model, using a separate analysis for each stage. The same model was applied to the SD of power for each stage, representing the stroke-to-stroke variability in power within a stage.

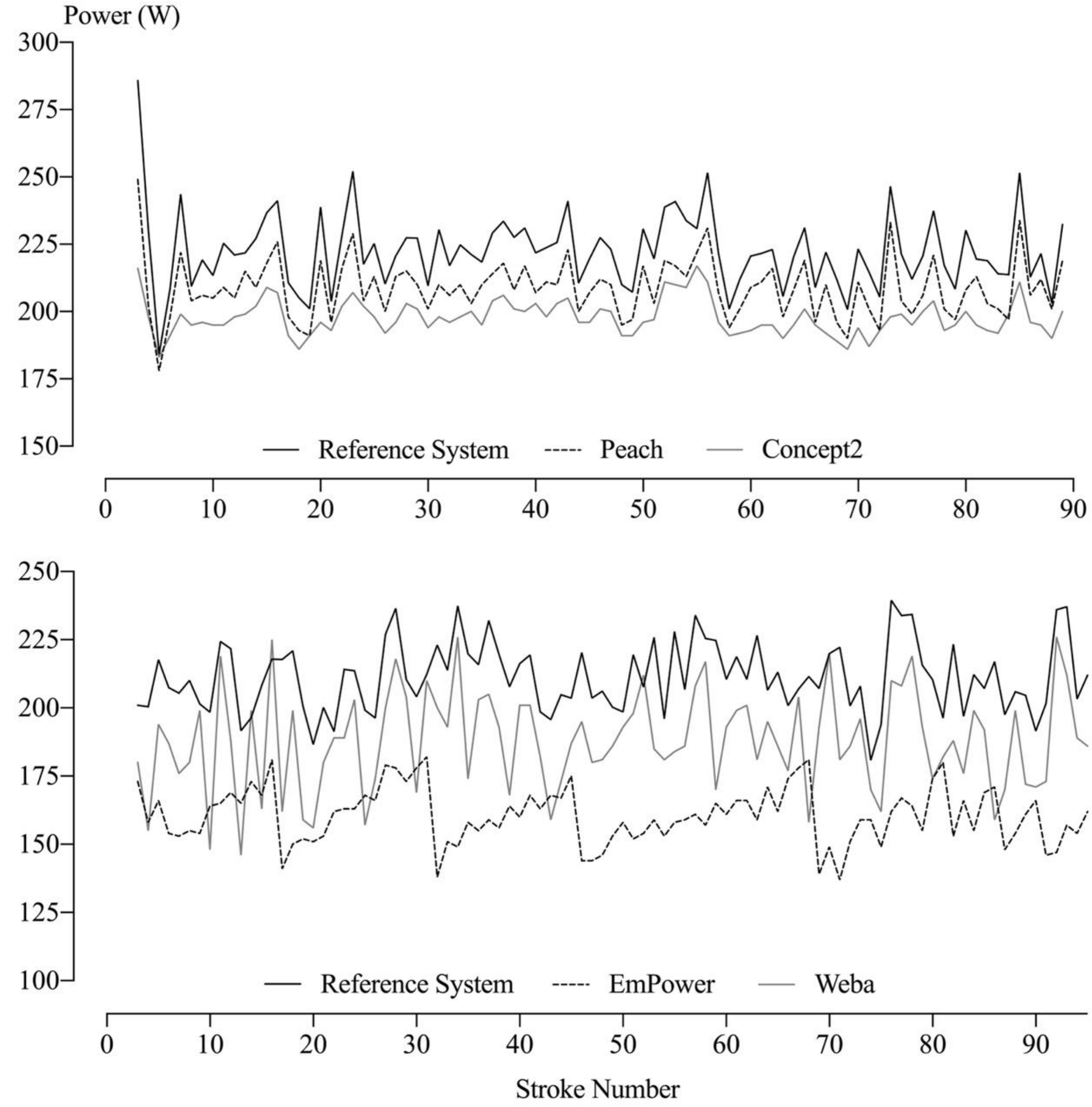

Figure 4.6. Power per stroke for each device during Stage 5 of two consecutive testing sessions by the same participant. Data for the Weba and Concept2 were recorded in every session but for reasons of clarity are not shown for the Weba (above) or the Concept2 (below).

The general linear mixed-model procedure (Proc Mixed) was used to perform the analysis in the Studio On-demand for Academics edition of the Statistical Analysis System (version 9.4, SAS Institute, Cary NC). The dependent variable was the log of the mean and the log of the log of the factor SD. The fixed effects were device identity and device identity interacted with Reference System power to estimate respectively systematic error (representing the difference in mean power from the Reference System for a given device) and proportional error (representing the change in mean error for a given change in the Reference System's mean power or the Reference System's stroke-to-stroke variability in power) for each device. With these fixed effects, a separate residual for each device (estimated as a variance and expressed as an SD) was specified to represent technical error of measurement (random session-to-session changes in error) of the device. Random effects of increasing complexity were added to the model to account for and reduce what turned out to be substantial residual variance. The final random effects (estimated as variances and expressed as SD) were: device identity interacted with unit identity (representing differences in error between units for Weba, Peach, or EmPower devices; a separate variance was estimated for each device); session identity (representing differences between the testing sessions that were experienced equally by the three devices in the given session and therefore potentially changes in the Reference System between sessions); and participant identity (representing differences between participants; a separate variance was estimated for each device, to allow for each device responding uniquely to each participant's rowing style). A random effect representing differences in proportional error between each unit of each device was also investigated; the effect was unclear for all devices but consistent with trivial for Peach and Weba, so this effect was not included in the final model. For the analysis of the SDs (stroke-to-stroke variations), random effects representing differences between participants and potential session-to-session differences arising from the Reference System are not presented, but are available on request, as are the residuals representing the technical error of measurement for the SDs of each device.

Plots of residuals vs predicteds were examined for outliers and evidence of non-uniformity. To ensure correct interpretation of the random effects and residuals, analyses of mean power were also performed by including data for an additional device simulating the Peach: the data for this device were those of the Reference System, but with added random error of 5% for each session, and with five units simulated by adding 3%, 6%, 9%, 12% and 15% to the Reference System values. Finally, to investigate the extent to which changes in error in each device between sessions (evident as the residuals) arose from random changes in the device, mean correlations of the residuals of each device with the other devices were computed for each stage (expected values of 0.00, if the session-to-session error arose entirely separately in each device), and mean correlations of the residuals of each stage with the other stages were computed for each device (expected values approaching 1.00, if the session-to-session error in each device was consistent across the stages in a given session).

A smallest substantial change in power of 1.0 % was assumed from the 1.0 % race-to-race variation in 2000-m race times of elite rowers (corresponding to a 0.3 % smallest substantial change in rowing velocity) and the assumption that power is proportional to velocity cubed (T. B. Smith & Hopkins, 2011). Corresponding magnitude thresholds were based on the factors for competitive performance (Hopkins et al., 2009) and are used to provide a practical description of the magnitude of error relative to the magnitude for a meaningful change in performance (i.e., the smallest substantial change in power); for positive changes in power these were <1.0 % trivial, ≥1.0 % small, ≥3.0 % moderate, ≥5.5 % large, ≥8.6 % very large, and ≥14 % extremely large; for negative changes the thresholds were >-1.0 % trivial, ≤-1.0 % small, ≤-2.9 % moderate, ≤-5.2 % large, ≤-8.0 % very large, and ≤-12 % extremely large. To evaluate the magnitudes of SDs representing between-unit differences in mean power and the residuals, the magnitude thresholds were one-half of those in the above scales (T. B. Smith & Hopkins, 2011): <0.5 % trivial, ≥0.5 % small, ≥1.5 % moderate, ≥2.7 % large, ≥4.2 % very large, and ≥6.7 % extremely large. Magnitudes of proportional error were assessed for a 10 % difference in Reference System mean power; the usual two between-subject SDs (Hopkins et al., 2009) was not appropriate, given the wide range in power between participants arising from the inclusion of males and females.

Magnitude thresholds for comparing the mean SDs of power (representing the mean stroke-to-stroke variability in power within a stage) were the usual factor thresholds for hazards and counts (Hopkins et al., 2009); for factor increases (which would occur when a device adds noise to the participant's stroke-to-stroke variability, as demonstrated by Weba in comparison to the refence system in Figure 4.6) the thresholds were <1.11 (11 %) trivial, ≥1.11 small, ≥1.43 (43 %) moderate, ≥2.0 (100 %) large, ≥3.3 (230 %) very large, and ≥10 (900 %) extremely large; for factor decreases (which would occur when a device lacks measurement sensitivity for stroke-to-stroke variations in power, as demonstrated by the Concept2 in comparison to the refence system in Figure 4.6) the thresholds were >0.90 (-10 %) trivial, ≤0.90 small, ≤0.70 (-30 %) moderate, ≤0.50 (-50 %) large, ≤0.30 (-70 %) very large, and ≤0.10 (-90 %) extremely large. To evaluate the magnitudes of SDs representing between-unit differences in the mean SD in power, the magnitude thresholds are one-half of those for factor increases: <1.05 (5.4 %) trivial, ≥1.05 small, ≥1.2 (20 %) moderate, ≥1.41 (41 %) large, ≥1.83 (83 %) very large, and ≥3.16 (220 %) extremely large. Magnitudes of proportional error were assessed for a two between-subject SD in the Reference System mean SD of power (Hopkins et al., 2009), because gender differences were not expected to affect between-subject differences in the SD expressed in percent units.

The thresholds for comparing the SDs were justified by using simulation (with spreadsheets) to investigate the extent to which noise and a loss in measurement sensitivity (apparent smoothing) for power per stroke modify effects involving power per stroke as either a predictor or a dependent variable. The effect of power per stroke as a predictor with added noise is attenuated by a factor equal to the square of the ratio of the SD of true power per stroke (represented by the Reference System) divided by the SD of the predictor (represented by the device), when the effect of the predictor is expressed per unit of the predictor (as stated by Hopkins et al., 2009); however, when expressed per 2 SD of the predictor, the effect is attenuated by the ratio of the SDs without squaring. Effects when power per stroke is a predictor with a lack of measurement sensitivity are *increased* by a factor equal to the ratio of the SD of true power per stroke divided by the SD of the predictor, when the effect of the predictor is expressed per unit of the predictor; however, when expressed per 2 SD of the predictor there is negligible attenuation of the effect (<5 %) when the ratio of measured/true SD is >0.7. For effects when power per stroke is a dependent variable with added noise, there is no modification of the effect magnitude (as stated by Hopkins et al., 2009). Effects when power per stroke is a dependent variable with a lack of measurement sensitivity are attenuated by a factor equal to the ratio of the SD of the dependent variable divided by the SD of true power per stroke, when the ratio is >0.7; for a reduction in measurement sensitivity (e.g., ratio of SDs = 0.6), the attenuation is a little greater than the ratio (0.65). In summary, noise or a lack of measurement sensitivity of power per stroke does not modify effects in two scenarios, but it modifies effects by factors given by the ratio of the SDs in three scenarios (effect attenuation in two, effect amplification in one) and by the square of the ratio in one scenario. We therefore opted to assess the effect of noise and a lack of measurement sensitivity by assessing the ratio of the SDs, and we used the thresholds for ratios of hazards and counts, since it seems reasonable to consider that modifications of an effect magnitude by a factor of 0.9 (or its inverse, 1.11) through to 0.1 (or its inverse 10) represent thresholds for small through to extremely large. Researchers should be aware that square roots of these thresholds will apply to a noisy predictor per unit of the predictor, but that there is no effect on the magnitude per two SD of a predictor with a modest lack of measurement sensitivity, and no effect on magnitude with a noisy dependent.

Sampling uncertainty in the estimates of effects is presented as 90% compatibility limits in the tables. For those who prefer a frequentist interpretation of sampling uncertainty, decisions about magnitudes accounting for the uncertainty were based on one-sided interval hypothesis tests, where an hypothesis of a given magnitude (substantial, non-substantial) was rejected if the 90% compatibility interval fell outside that magnitude (Aisbett et al., 2020; Hopkins, 2020). P-values for the tests were the areas of the sampling distribution of the effect (t for means, z for random-effect variances, chi-squared for residual variances) falling in the hypothesised magnitude, with the distribution centered on the observed effect. Hypotheses of inferiority (substantial negative) and superiority (substantial positive) were rejected if their respective p-values ($p_{–}$ and p_{+}) were <0.05; rejection of both hypotheses represents a decisively trivial effect in equivalence testing. For residual variances, only the tests of superiority and non-superiority were relevant. When only one hypothesis was rejected, the p-value for the other hypothesis, when >0.25, was interpreted as the posterior probability of a substantial true magnitude of the effect in a reference-Bayesian analysis with a minimally informative prior (Hopkins, 2019) using the following scale: >0.25, possibly; >0.75, likely; >0.95, very likely; >0.995, most likely (Hopkins et al., 2009); the probability of a trivial true magnitude ($1 – p_{–} – p_{+}$) was also interpreted, when >0.25, with the same scale. Probabilities were not interpreted for effects that were unclear (those with inadequate precision at the 90% level, defined by failure to reject both hypotheses, $p_{–}$>0.05 and p_{+}>0.05). Effects with adequate precision at the 99% level ($p_{–}$<0.005 or p_{+}<0.005) are in bold in the tables; these represent effects that have a conservative low risk of error or noise. The hypothesis of non-inferiority (non-substantial-negative) or non-superiority (non-substantial-positive) was rejected if its p value ($p_{N–} = 1 – p_{–}$ or $p_{N+} = 1 – p_{+}$) was <0.05, representing a decisively substantial effect in minimal-effects testing: very likely or most likely substantial.

4.4 Results

The power per stroke throughout a stage for the five devices is exemplified in Figure 4.6. The mean and SD (representing the stroke-to-stroke variation in power) of the individual values of power per stroke in Figure 4.6 for each device (along with those of all the other stages and testing sessions) provided the data for the subsequent analyses.

The mean power of each of the five devices across all testing sessions and participants for each stage is shown in **Figure 4.7** (top), with SD bars representing between-unit differences in the mean power. The mean stroke rates performed for each stage were: 30-s test, 43.8 ± 7.0 (stroke·min^{-1}, mean ± SD); Stage 1, 18.0 ± 1.0; Stage 2, 19.4 ± 1.0; Stage 3, 21.2 ± 1.2; Stage 4, 23.0 ± 1.4; Stage 5, 24.8 ± 3.0; Stage 6, 27.3 ± 1.7; Stage 7, 32.7 ± 1.9.

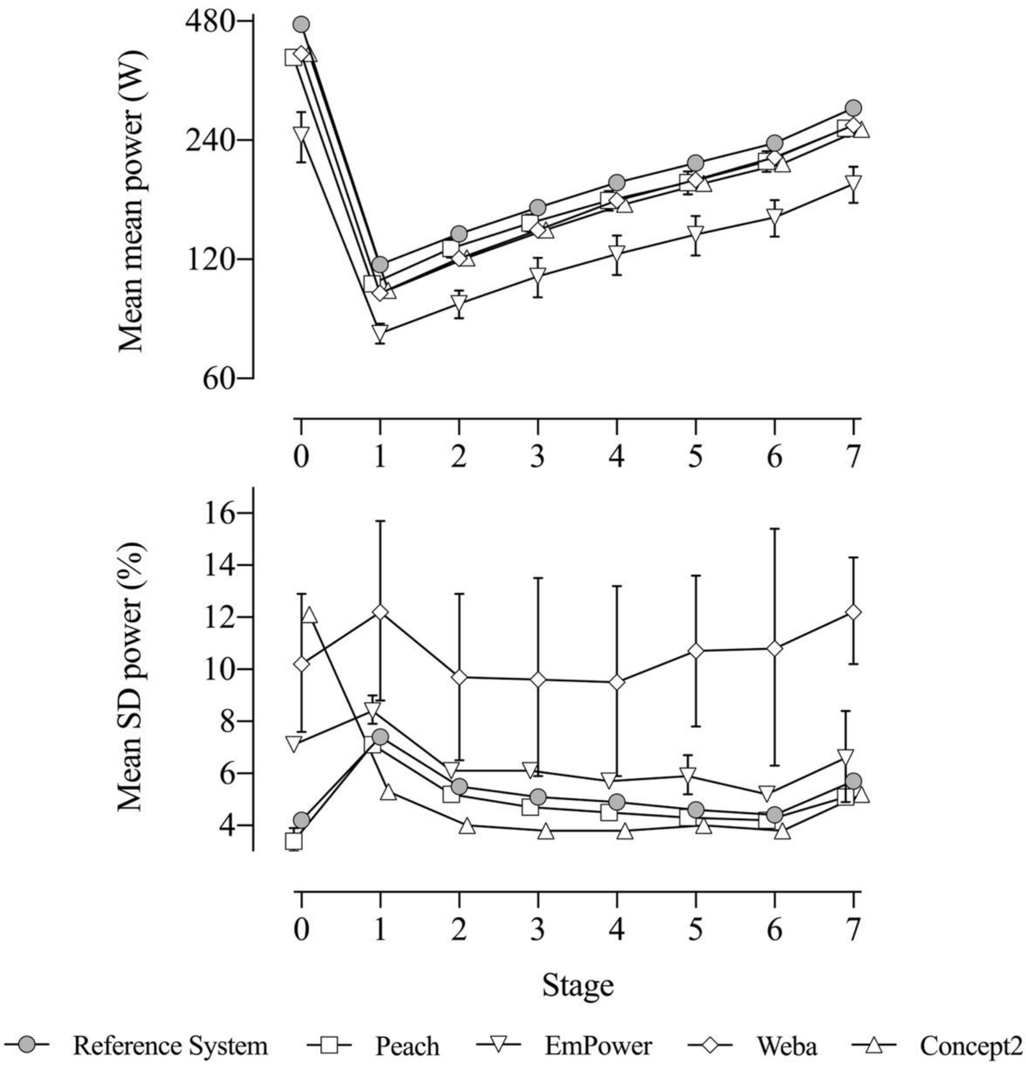

Figure 4.7. Means of the mean (top) and SD (bottom) of power for each device in each stage for all the testing sessions. SD bars represent between-unit SD for the means and SD. The Reference System and the Concept2 have no SD bars, as only one unit was tested. SD bars on the bottom plot are omitted from some stages for Peach and EmPower, reflecting negative variance. Stage 0 represents the 30-s maximal test.

4.4.1 Systematic error

The difference in mean power from the Reference System (representing systematic error) across the eight stages were all decisively substantial and negative (rejection of the non-inferiority hypotheses, p_{N-} <0.05), and are presented in Table 4.1. Magnitudes were very large in most stages for Peach, extremely large for EmPower, and mostly very large to extremely large for Weba and the Concept2. Within each device, there is a consistent percent error across Stages 1 to 7, as shown by the near-equal spacing from Reference System values with a log scale on the y-axis in Figure 4.7. All devices showed relatively greater systematic error in the 30-s test.

Table 4.1. Mean systematic error across the stages for Peach, EmPower, Weba, and the Concept2.

Data are mean (%), ±90% compatibility limits, with observed magnitude and p values for inferiority and superiority tests ($p_{–}/p_{+}$).

	Peach	EmPower	Weba	Concept2
30-s test	**-16.9, ±2.7; e.large****** >0.999/<0.001	**-47.7, ±8.1 e.large****** 0.999/0.001	**-15.4, ±3.9; e.large****** 0.996/0.003	**-15.2, ±0.8; e.large****** >0.999/<0.001
Stage 1	**-10.5, ±3.4; v.large****** 0.999/0.001	-32.3, ±9.1; e.large*** 0.98/0.02	-15.5, ±6.0; e.large*** 0.99/0.01	**-13.9, ±1.6; e.large****** >0.999/<0.001
Stage 2	**-7.9, ±4.3; large***** 0.99/0.005	**-32.9, ±7.1; e.large***** 0.995/0.005	**-13.4, ±3.9; e.large****** 0.996/0.003	**-13.0, ±1.7; e.large****** >0.999/<0.001
Stage 3	**-8.8, ±4.0; v.large***** 0.995/0.002	-32.2, ±9.5; e.large*** 0.99/0.01	-12.4, ±4.1; v.large*** 0.99/0.01	**-12.3, ±0.6; v.large****** >0.999/<0.001
Stage 4	**-10.0, ±4.6; v.large***** 0.99/0.003	-33.2, ±9.5; e.large*** 0.98/0.02	**-10.5, ±2.4; v.large****** >0.999/<0.001	**-11.9, ±0.7; v.large****** >0.999/<0.001
Stage 5	**-11.3, ±5.9; v.large***** 0.99/0.005	-33.6, ±14.3; e.large*** 0.98/0.02	**-9.5, ±3.1; v.large****** 0.998/0.001	**-11.2, ±0.7 v.large****** >0.999/<0.001
Stage 6	**-10.1, ±5.1; v.large***** 0.99/0.003	-34.5, ±9.8; e.large*** 0.99/0.01	**-7.9, ±3.0; large****** 0.996/0.002	**-11.3, ±0.6; v.large****** >0.999/<0.001
Stage 7	**-11.2, ±4.2; v.large****** 0.998/0.001	-35.4, ±8.5; e.large*** 0.99/0.01	**-9.6, ±3.1; v.large***** 0.99/0.004	**-11.6, ±0.6 v.large****** >0.999/<0.001

Scale of magnitudes: >-1 %, trivial; ≤-1 %, small; ≤-2.9 %, moderate (mod); ≤-5.2 %, large; ≤-8.0 %, very large (v.large); ≤-12.4 %, extremely large (e.large).
Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely, ****most likely.
*** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005 respectively).
Effects in **bold** have adequate precision at the 99% level (p<0.005).

Differences from the Concept2 in mean power across the eight stages are presented in Table 4.2. Magnitudes were trivial to moderate and mostly positive for Peach, but most were either unclear (the superiority and inferiority hypotheses were not rejected, p_{+} and $p_{–}$ >0.05) or were only likely substantial (rejection of only the inferiority hypotheses, $p_{–}$ <0.05). In comparison to the Concept2, mean differences in power for EmPower were negative, extremely large, and decisively substantial. Mean differences in power from the Concept2 for Weba ranged from positive to negative and were trivial to moderate, but most were unclear.

Table 4.2. Differences from the Concept2 in mean systematic error across the stages for Peach, EmPower, and Weba. Data are mean (%), ±90% compatibility limits, with observed magnitude and p values for inferiority and superiority tests ($p_{–}$/p_{+}).

	Peach	EmPower	Weba
30-s test	-2.0, ±3.2; small 0.72/0.06	**-38.3, ±9.6; e.large****** 0.998/0.001	-0.2, ±4.3; trivial 0.35/0.27
Stage 1	3.9, ±4.2; moderate** 0.03/0.89	-21.4, ±8.0 e.large*** 0.98/0.01	-1.9, ±6.7; small 0.61/0.20
Stage 2	5.9, ±5.0; large** 0.02/0.94	-22.9, ±7.9; e.large*** 0.99/0.01	-0.5, ±4.3; trivial 0.41/0.24
Stage 3	4.0, ±4.6; moderate** 0.04/0.88	-22.8, ±10.8; e.large*** 0.98/0.02	-0.1, ±4.6; trivial 0.32/0.28
Stage 4	2.1, ±5.2; small 0.14/0.66	-24.2, ±12.5; e.large*** 0.97/0.03	1.6, ±2.8; small 0.06/0.65
Stage 5	0.0, ±6.6; trivial 0.39/0.38	-25.2, ±15.9; e.large*** 0.96/0.03	1.9, ±3.5; small 0.08/0.69
Stage 6	1.4, ±5.8; small 0.23/0.55	-26.2, ±10.9; e.large*** 0.98/0.02	3.8, ±3.4; moderate** 0.02/0.93
Stage 7	0.4, ±4.8; trivial 0.29/0.42	-26.9, ±9.6; e.large*** 0.99/0.01	2.2, ±3.3; small 0.05/0.79

Scale of magnitudes: <1 and >-1 %, trivial; ≥1 or ≤-1 %, small; ≥3.0 or ≤-2.9 %, moderate (mod); ≥5.5 or ≤-5.2 %, large; ≥8.5 or ≤-8.0 %, very large (v.large); ≥14.2 or ≤-12.4 %, extremely large (e.large).

Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely, ****most likely.

*** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005 respectively).

Likelihoods are not shown for effects that were unclear at the 90% level (failure to reject any hypotheses: p>0.05).

Effects in **bold** have adequate precision at the 99% level (p<0.005).

4.4.1.1 Proportional error in systematic error

Proportional error for a change in power, representing the percentage change in mean error for a 10 % change in the Reference System mean power, was estimated for each stage for Peach, EmPower, Weba, and Concept2. Magnitudes of proportional error for a change in power were trivial in most stages for Peach (-2.8 % for the 30-s test, and -0.7 to 0.2 % for the other stages) and were either unclear or only possibly or likely trivial for most stages. For EmPower, proportional error was trivial to moderate (-4.4 % for the 30-s test, and -2.2 to -0.6 % for the other stages) and were either unclear or only possibly or likely substantial for most stages. Proportional error was trivial for Weba (-0.6 % for the 30-s test, and -0.6 to -0.3 % for the other stages) and most effects were possibly or likely trivial. For the Concept2 proportional error was trivial in most stages (0.8 % for the 30-s test, and -1.6 to 0.7 % for the other stages) with adequate precision that was likely trivial for most stages.

4.4.1.2 Between-unit differences in systematic error

Between-unit differences in mean power (the SD bars in Figure 4.7, top) summarise the relative error of the units for a given device, reflecting the degree of differences in systematic error between the units. Only one Concept2 unit was assessed, so no between-unit differences were established for this device. With the exception of one stage for Weba, all the SDs were positive, but unclear. Despite being unclear, the random-effect solutions for the device units (representing the systematic error of each unit) showed evidence of consistent relative error across the stages for most units (data not shown). The observed magnitudes for between-unit differences in mean power were very large in most stages for Peach (an SD of 1.8 % for the 30-s test, and 3.6 to 7.6 % for the other stages), extremely large in most stages for EmPower (17 % for the 30-s test, and 3.5 to 9.3 % for the other stages), and trivial to large for Weba (1.3 % for the 30-s test, and -0.3 to 3.9 % for the other stages).

4.4.1.3 Between-session and between-participant error

The SD representing error potentially introduced by the Reference System between sessions were unclear in all but one stage. Observed magnitudes were positive in most stages and small to moderate (-1.6 % for the 30-s test, and 1.1 to 1.8 % for the other stages).

Differences in error between participants, estimated as a SD for each device, were unclear for most stages. The observed differences were positive and moderate to very large for Peach (5.0 % for the 30-s test, and 2.1 to 4.5 % for the other stages), negative and extremely large for EmPower (-10 % for the 30-s test, and -7.0 to -7.8 % for the other stages), positive in most stages and small to moderate for Weba (1.6 % for the 30-s test, and -0.5 to 4.2 % for the other stages), and positive and small in most stages for the Concept2 (0.9 % for the 30-s test, and 0.8 to 3.7 % for the other stages).

The residual SD representing the technical error of measurement in mean power between sessions (random session-to-session changes in error) was decisively substantial for all stages in Peach, EmPower, Weba, and for most stages for the Concept2, as shown in Table 4.3. Observed magnitudes were large to very large for Peach, extremely large for EmPower and Weba, and small to large for the Concept2.

Table 4.3. Technical (residual) error of measurement representing session-to-session error for mean power recorded by Peach, EmPower, Weba, and the Concept2.

Data are SD (%), ±90% compatibility limits, with observed magnitude and p values for the superiority test (p_+).

	Peach	EmPower	Weba	Concept2
30-s test	5.1, ±1.7 v.large**** >0.999	26.0, ±9.3 e.large**** >0.999	12.4, ±2.4 e.large**** >0.999	3.5, ±1.2 large**** >0.999
Stage 1	6.6, ±2.0 v.large**** >0.999	18.6, ±5.7 e.large**** >0.999	11.5, ±2.1 e.large**** >0.999	0.9, ±0.0 small** 0.90
Stage 2	4.1, ±1.5 large**** >0.999	18.0, ±5.7 e.large**** >0.999	9.6, ±1.7 e.large**** >0.999	1.3, ±1.5 small**** >0.999
Stage 3	4.3, ±1.5 v.large**** >0.999	18.6, ±6.7 e.large**** >0.999	9.6, ±1.8 e.large**** >0.999	0.5[a] trivial -
Stage 4	4.7, ±1.5 v.large**** >0.999	17.9, ±6.4 e.large**** >0.999	7.6, ±1.4 e.large**** >0.999	1.1, ±3.3 small*** 0.99
Stage 5	4.5, ±1.7 v.large**** >0.999	18.9, ±7.2 e.large**** >0.999	7.7, ±1.4 e.large**** >0.999	1.4, ±1.3 small**** >0.999
Stage 6	4.0, ±1.4 large**** >0.999	17.7, ±6.2 e.large**** >0.999	7.8, ±1.4 e.large**** >0.999	1.6 ±1.1 moderate**** >0.999
Stage 7	4.8, ±1.7 v.large**** >0.999	17.3, ±6.0 e.large**** >0.999	7.2, ±1.4 e.large**** >0.999	1.4, ±5.8 small**** 0.997

Scale of magnitudes: <0.5 %, trivial; ≥0.5 %, small; ≥1.5 %, moderate (mod); ≥2.7 %, large; ≥4.2 %, very large (v.large); ≥6.9 %, extremely large (e.large).
[a]The mixed model failed to produce compatibility limits for this residual.
Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely, ****most likely.
*** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005 respectively).
Reference-Bayesian likelihoods of trivial change: [0]possibly; [00]likely; [000]very likely, [0000]most likely.

Not shown in the tables are the fixed and random effects for the simulated device, which were used to ensure correct interpretation of the mixed model. The effects for the simulated device, including the residuals, were all consistent with the simulated values. The mean correlations of the technical error residuals of each device with the other devices for each stage ranged from -0.22 to 0.16; this range is consistent with sampling variation when the expected value is 0.00, if the session-to-session error arose entirely separately in each device. The mean correlations of the residuals of each stage with the other stages for each device ranged from 0.92 to 0.98 for the simulated device (where the expected value is 1.00, if the session-to-session error in each device was consistent across the stages in a given session); the ranges for the other devices were: Peach, 0.29 to 0.77; Empower, 0.73 to 0.92; Weba, 0.30 to 0.73; and Concept2, 0.64 to 0.89. For each device, the lowest mean correlation occurred for the 30-s stage; without this stage the mean correlations were all ~0.8 to 0.9, which reflects consistent error across the stages.

4.4.2 Mean SD of power representing random error

The mean SD for the Reference System (bottom in Figure 4.7) shows that the participants' true stroke-to-stroke variability in power output was lowest in the 30-s test, highest in Stage 1, declined through Stages 2-6, then increased again for the maximal effort in Stage 7. Differences of each device from the Reference System in the mean SD of power are evident in Figure 4.7 and are presented in Table 4.4. Positive differences are consistent with additional noise in stroke-to-stroke variation in power (EmPower and Weba, as demonstrated in comparison to the refence system in Figure 4.6), and negative differences are consistent with a lack of measurement sensitivity (Peach and the Concept2, as demonstrated in comparison to the refence system in Figure 4.6). Magnitudes were trivial to small and negative for Peach and were possibly, likely, or decisively trivial or substantial. Differences from the Reference System in the SD for EmPower were positive and trivial to moderate and possibly or likely substantial in most stages. For Weba, differences in the SDs from the Reference System were positive, moderate to large and decisively substantial in most stages. The Concept2 showed a positive and large mean SD difference from the Reference System for the 30-s test, but negative and mostly small differences for the other stages that were possibly or decisively substantial.

Table 4.4. Differences in the mean SD of power from the Reference System across the stages for Peach, EmPower, Weba, and the Concept2. Data are mean (%), ±90% compatibility limits, with observed magnitude and p values for inferiority and superiority tests ($p_{–}/p_{+}$).

	Peach	EmPower	Weba	Concept2
30-s test	**-16, ±11; small**** 0.85/0.005	**57, ±27; moderate****** <0.001/0.998	139, ±110; large*** 0.01/0.98	**177, ±46; large****** <0.001/>0.999
Stage 1	**-3.0, ±4.0; trivial^{0000}** 0.004/<0.001	14, ±16; small*^{0} 0.02/0.64	61, ±74; moderate** 0.03/0.93	**-27.8, ±3.6; small****** >0.999/<0.001
Stage 2	**-4.4, ±3.6; trivial^{000}** 0.009/<0.001	**9.7, ±5.9; trivial^{0}*** <0.001/0.35	73, ±84; moderate** 0.03/0.94	**-27.9, ±4.6; small****** >0.999/<0.001
Stage 3	**-6.5, ±4.0; trivial^{00}** 0.07/<0.001	**20, ±13; small**** <0.001/0.88	88, ±82; moderate*** 0.02/0.97	**-24.3, ±8.2; small***** 0.99/<0.001
Stage 4	**-6.4, ±5.1; trivial^{00}** 0.11/<0.001	**15.5, ±8.4; small**** <0.001/0.81	91, ±78; moderate*** 0.02/0.97	**-20.8, ±9.6; small*^{0}** 0.96/<0.001
Stage 5	**-5.2, ±5.4; trivial^{00}** 0.07/<0.001	29, ±26; small** 0.09/0.90	126, ±95; large*** 0.01/0.99	**-13.1, ±11.4; small*^{0}** 0.68/0.003
Stage 6	**-3.9, ±5.3; trivial^{000}** 0.03/<0.001	**17, ±14; small**** 0.001/0.77	136, ±148; large*** 0.02/0.97	**-13.8, ±10.9; small*^{0}** 0.90/0.01
Stage 7	**-9.7, ±6.9; trivial^{0}*** 0.47/<0.001	15, ±29; small 0.05/0.60	109, ±65; large*** 0.01/0.99	**-7.2, ±8.1; trivial^{0}*** 0.27/0.002

Scale of magnitudes: <11 and >-10 %, trivial; ≥11 or ≤-10 %, small; ≥43 or ≤-30 %, moderate (mod); ≥100 or ≤-50 %, large; ≥230 or ≤-70 %, very large (v.large); ≥900 or ≤-90 %, extremely large (e.large).

Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely, ****most likely.

*** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005 respectively).

Reference-Bayesian likelihoods of trivial change: ^{0}possibly; ^{00}likely; ^{000}very likely, ^{0000}most likely.

^{000} and ^{0000} indicate rejection of the superiority and inferiority hypothesis (p_{-} and p_{+} <0.05 and <0.005 respectively).

Effects in **bold** have adequate precision at the 99% level (p<0.005).

4.4.2.1 Proportional error in the mean SD of power

Proportional error in the SD of power for a 2-SD change in the Reference System was likely trivial for Peach in most stages (2.7 % for the 30-s test, and -5.8 to 1.1 % for the other stages), small and likely substantial in most stages for EmPower (-43 % for the 30-s test, and -24 to -10 % for the other stages), small and decisively substantial in most stages for the Concept2 (-53 % for the 30-s test, and -29 to -0.4 % for the other stages), and moderate and decisively substantial in most stages for Weba (-43 % for the 30-s test, and -42 to -23 % for the other stages).

4.4.2.2 Between-unit differences in the mean SD of power

Between-unit differences in the mean SD of power are illustrated by the SD bars in Figure 4.7 (bottom). Positive between-unit variance for Peach is evident in six stages and was likely or decisively trivial in most of these stages (SDs of 13 % for the 30-s test, and 0.6 to 3.3 for the other stages). Positive between-unit variance for EmPower is evident in three stages and ranged from small to moderate (8.6, 12, and 24 % for Stages 1, 5, and 7 respectively) but were unclear. The other stages for Peach and EmPower showed negative variance. Positive between-unit variance was observed in all stages for Weba and was moderate in most stages (25 % for the 30-s test, and 19 to 40 % for the other stages); although the estimates all were unclear, the random-effect solutions for Weba units showed that specific units tended to have consistent error across the stages (data not shown). As with the analysis of means, no between-unit differences were possible for the Concept2.

4.5 Discussion

This is the first study to assess the concurrent validity of power output from on-water rowing instrumentation systems. Additionally, the comparison of power from on-water instrumentation systems to that from a Concept2 Model D rowing ergometer had not been investigated previously and provides valuable insight into differences between on- and off-water measures of power in rowing. The devices were assessed over a wide range of intensities and stroke rates, and in an on-water rowing-specific range of motion for Peach, EmPower, and Weba, promoting the applicability of findings from this study for use of these devices on the water. Negative systematic error was evident for all devices in comparison to the Reference System, whereby mean power was lower in all devices than the Reference System; systematic error was of similar magnitude for Peach, Weba, and the Concept2, but was greater in EmPower. Less measurement sensitivity of stroke-to-stroke variations in power were observed in comparison to the Reference System for the Concept2 and Peach, but were negligible in Peach where concurrent variations in power with the Reference System were observed (Figure 4.6). EmPower and Weba added random error (noise) to stroke-to-stroke variations in power in comparison to the Reference System (Figure 4.6). There was some evidence of substantial between-unit differences in mean power for Peach, EmPower and Weba, but the SDs representing between-unit differences all were unclear. Between-unit differences were not apparent in the SD of power (i.e., units did not differ in their measurement sensitivity or noise) for Peach and EmPower, whereas Weba units differed in their amount of noise, but again all the SDs were unclear.

4.5.1 Systematic error

Differences from the Reference System in device mean power inform potential systematic error for the given device. It should be noted that the Reference System does not provide a criterion measure of power, rather, concurrent validity in comparison to the Reference System is reported. Calculation of power from the Reference System includes a correction for force relative to oar angle (as detailed in the Methods section), where error for the Reference System may have been introduced. The consistent ~10 % difference in mean power for Peach, Weba, and the Concept2 from the Reference System may therefore reflect positive systematic error for the Reference System whereby true power is closer to that of Peach, Weba, and the Concept2. Only the Concept2 has been investigated previously for its validity of power output, where negative systematic error of ~7 % was found in comparison to instrumentation similar to that used in the current study (Boyas et al., 2006). Most of the apparent systematic error in the current study may therefore be coming from the devices rather than the Reference System. The greater negative systematic error for EmPower in comparison to the other devices may be related to the stepped pattern in power output sometimes evident during testing (as illustrated in Figure 4.6 for EmPower).

It should be acknowledged that although the Swingulator simulates on-water rowing, it is essentially a stationary ergometer and therefore differences exist in the application and measurement of power by the devices on the Swingulator in comparison to that on-water.

On-water no fixed point of force transfer exists and the acceleration of the rower's centre of mass occurs relative to the acceleration of the boat-rower system on-water (Kleshnev, 2002), with mechanical power exchanged at the footplate and oar handle (Hofmijster et al., 2018). In comparison, the rower's centre of mass is accelerated along the slide via reactive forces occurring from the application of force at a fixed footplate on stationary ergometers, and little mechanical power is lost from the system (Hofmijster, van Soest, & De Koning, 2008). It is therefore possible that the systematic error established in this study differs to that for Peach, EmPower and Weba devices when used on-water and therefore further research examining the validity of power output from these devices on-water is warranted. Nevertheless, the calculation of power on-water from handle force and oar angular velocity has been shown to underestimate the true mechanical power generated by the rower by at least 10% (Hofmijster, Lintmeijer, Beek, & van Soest, 2018).

The location of measurement and calculation of power used by each device is expected to account for some of the differences in systematic error observed between devices. The Concept2 calculates power from the acceleration of the flywheel each stroke and the stroke time (Boyas et al., 2006). Power is calculated by the Weba from the moment of force applied at the handle, which is derived from the deflection of the oar shaft measured at the inboard (Kleshnev, 2010b). The Peach system calculates power from measures of gate angular velocity, gate force in the direction of the boat's long axis, and the ratio of the oar outboard (distance from the collar to blade tip) to total length. EmPower is also located at the gate and is assumed to calculate power with a similar method to Peach, but uses a magnetometer to detect gate angle, where a potentiometer is used by Peach. Despite the differences in location of force measurement and methods of power calculation between the devices, their systematic bias is expected to be somewhat similar given they are each providing a measure of the total mechanical power applied to the handle.

Differences from the Concept2 in mean power for Peach, EmPower, and Weba can be used by practitioners to inform expected differences between on- and off-water power outputs, and the extent to which differences are related to device measurement or the technical demand of on-water rowing. Power output at high intensities is lower on-water than on a Concept2 ergometer over the same test duration (Vogler et al., 2010). Over a 2000 m time trial, a ~15% lower mean power has been observed on-water with Peach than for the same test on a Concept2 ergometer (personal observations). However, differences in mean power between Peach and the Concept2 in the current study were only ~1 % for high intensities (Stages 6 and 7). The smaller difference between the Peach and Concept2 at high intensities in the current study than that observed when these devices are used in the field suggests the systematic error differences between the two devices contribute only a small portion of the overall difference between on- and off-water power. The remaining discrepancy between on- and off-water power that is not related to systematic error differences between the devices may therefore reflect a reduction in the power that is applied on-water in comparison to that applied on a Concept2 ergometer. The differing technical demand of on-water rowing in comparison to rowing on an ergometer (Kleshnev, 2005) may constrain the power applied during high intensity efforts on-water, as demands such as the entry and exit of the oar from the water will influence the power applied on water, but do not contribute to a rowing stroke on a Concept2 ergometer.

4.5.1.1 Proportional error in systematic error

The systematic error magnitudes reported are relative to the corresponding mean power per stage, and therefore may differ at different magnitudes of power. Proportional error (the change in systematic error for a 10 % change in mean power) represents the relationship between power and systematic error, enabling practitioners to estimate the relative systematic error for a given power output, such as during a race start or short high-intensity intervals where power output is very high. Proportional error was evident only for Peach and EmPower, and only for the 30-s test, where it was negative. Negative proportional error would produce a greater underestimation of power in comparison to the Reference System at higher power outputs, which is evident in the greater negative systematic error observed for the 30-s test in comparison to the other stages for Peach and EmPower in Table 4.1. It is possible that the proportional error for the 30-s test in Peach and EmPower is related to the location of measurement of these devices at the gate (Figure 4.1), as proportional error was consistently trivial for Weba and the Concept2 (which were located at different positions on the Swingulator system). Although rowing performance tests rarely encompass durations as short as 30 s, practitioners should be aware of the negative proportional error introduced by Peach and EmPower at very high power outputs.

4.5.1.2 Between-unit differences in systematic error

Based on the between-unit differences in mean power, use of the same unit for repeated measurements or comparing rowers is recommended to remove any potential error introduced by individual units. Although between-unit differences were unclear, specific units showed consistent error across the stages, indicating real differences exist between units. Furthermore, the magnitude of between-unit differences ranged up to large or extremely large for all devices. The unclear effects representing between-unit differences is due not only to the limited number of units assessed for each device, but also to the substantial session-to-session technical error of measurement (the random variation in mean power arising between sessions), which reduced the ability to partition error to specific units.

4.5.1.3 Between-session and between-participant error

Differences in mean power between sessions, representing the overall technical error of measurement, was partitioned via random effects into error introduced by the Reference System across all devices in each session (~1 %), error arising from different participants with each device (Peach ~3.5 %, EmPower ~ -8 %, Weba ~3 %, Concept2 ~2 %), and the residual technical error of measurement (i.e., the error introduced by each device in each session; Peach ~4.5 %, EmPower ~19 %, Weba ~9 %, Concept2 ~1.5 %). Together the error introduced by these three sources (the Reference System, that for different participants, and the residual technical error of measurement) reflect the total error introduced between sessions. Although mostly unclear, the error introduced by the Reference System between sessions was smallest of these three random effects and would represent only a small fraction of the overall technical error of measurement. The Reference System was therefore reliable relative to the other devices. Although the Reference System is not a criterion or gold-standard measure of power in the current study (rather it provides a comparative measure for assessing the concurrent validity of the other devices), the error arising from a criterion measure is an important component of the total error observed in validity studies that is often overlooked, and should be considered in future research examining device validity.

The extent to which device error differed between participants was generally unclear, but at least this sample may provide insight into the effect of different rowing styles on device measurement. The positive between-participant differences for Peach, Weba and the Concept2 may reflect differences in the error introduced by these devices when measuring power from differing rowing styles. Differences between participants in their pattern of force application, catch and finish angles (or chain position in the case of the Concept2), drive phase durations, or recovery phase durations could be factors contributing to between-participant differences in systematic error. However, further research is needed to better understand the differences in device error arising between participants and whether rowing style and device error are related. The negative between-participant differences for EmPower imply that more error is introduced when testing the same participant (i.e., the noise added to stroke-to-stroke variations in power) than when testing different participants, which is likely related to the stepped pattern in power output occasionally occurring within a stage for EmPower (as illustrated in Figure 4.6).

The correlations between the residuals supported the interpretation of the residuals as technical error of measurement arising independently in each device between sessions. In reliability studies, technical error of measurement combines with biological variability (e.g., variability in the power a participant can produce between testing sessions) to give the typical or standard error of measurement in such studies. The residual technical error observed here should therefore be smaller than the typical error observed elsewhere in reliability studies. However, the ~4.5 % technical error of measurement observed for Peach is larger than the typical (standard) error of measurement of 1.3 to 2.2 % found for Peach between three 500-m trials in elite scullers (Coker, 2010). The ~1.5 % technical error of measurement observed for the Concept2 lies within the range of the 1.3 % and 2.8 % standard error of measurement values reported for 2000-m and 500-m test distances on the Concept2 (Soper & Hume, 2004b), but would allow for little biological variability between tests. It is possible that the stationary testing set-up on the Swingulator in the present study could contribute to technical error in some way, at least for Peach and the Concept2, that would not arise when the devices are used as intended, either on-water (in the case of Peach, and possibly also EmPower and Weba), or without attachment to the Swingulator (in the case of the Concept2).

4.5.2 Mean SD of power representing random error

The shallow "U" shape across Stages 1 to 7 illustrated by the Reference System in its mean SD of power in Figure 4.7 (bottom) demonstrates that the participants' true stroke-to-stroke variability in power output decreased from Stages 1 through 6. The reduction in variability, particularly over Stages 1 to 3, is likely due to the difficulty associated with maintaining a consistent power output when the prescribed power is easier than the participants are familiar with. The increase in participant variability in Stage 7 may reflect pacing strategy in this maximal stage, such as a fast start and fast finish, or the inability to maintain a desired target power output. The least stroke-to-stroke variability was evident in the 30-s test (Stage 0), which was likely due to the short test duration, where pacing strategy and fatigue have limited contribution.

The positive differences from the Reference System in the mean SD of power for EmPower and Weba represent random error (noise) in the signal output of these devices. The small to moderate random errors for EmPower would produce modest attenuation of rowing performance predicted by power per stroke for submaximal and maximal intensities over 4 min, but a considerable attenuation of effects for maximal intensities over short durations (~30 s). The Weba would produce considerable attenuation of rowing performance predicted by power per stroke over all intensities assessed in this study. These attenuations would reduce the ability to detect true effects with power per stroke as a predictor.

Peach appeared to closely follow the stroke-stroke variation in power measured by the Reference System (as shown in Figure 4.6), although the analysis of the mean SD of power indicated a small amount of measurement sensitivity was lost in comparison to the Reference System. The mostly trivial difference in measurement sensitivity would result in little attenuation of relationships between power per stroke and rowing performance. Future research investigating individual stroke power (if the individual strokes could be aligned consistently) would enable the partitioning of stroke-to-stroke variation in power into the variation arising from the participant, random error (if any) in the Reference System, and any lack of measurement sensitivity (as negative variance) in Peach.

The Concept2 demonstrated a reduced measurement sensitivity in comparison to the Reference System, which improved from Stages 1 to 7, whereas considerable random error was apparent for the 30-s test. Inspection of the stroke-to-stroke data for the Concept2 revealed greater differences from the Reference System over the first ~5 strokes due to a gradual increase in power from the Concept2 at the start of each stage. These findings are consistent with those of Boyas et al. (2006), who found a reduction in the magnitude of negative systematic error for the Concept2 when they excluded the first three strokes from analysis. The gradual increase in power demonstrated by the Concept2 at the start of each stage (when the flywheel is stationary) likely reflects the increase in flywheel velocity due to the inertia of the flywheel, given that the acceleration of the flywheel is used to calculate power (Boyas et al., 2006; Dudhia, 2017). The effect of a lack of measurement sensitivity would therefore be reduced in later stages, as initial differences from the Reference System at the start of the stage contribute a smaller proportion of the total number of strokes per stage as stroke rate increases. The lack of measurement sensitivity observed for the Concept2 would result in small attenuations of rowing performance predicted by power per stroke.

4.5.2.1 Proportional error in the mean SD of power

The mostly trivial proportional error in the SD of power for Peach showed that there was reasonable consistency in the variation of power per stroke in comparison to the Reference System (as illustrated in Figure 4.6). The negative proportional error in the SD of power for EmPower and Weba represents a reduction in the magnitude of noise introduced to stroke-to-stroke measures of power by these devices when true (Reference System) stroke-to-stroke variation is higher. The negative proportional error observed for the Concept2 probably represents a decrease in measurement sensitivity at higher values of stroke-to-stroke variation, which will have some explanation in terms of the detection of fluctuations in flywheel velocity.

4.5.2.2 Between-unit differences in the mean SD of power

The occurrence of both positive and negative variance for between-unit differences in the mean SDs for Peach and EmPower likely arise from sampling variation, whereby a true variance of practically zero can be expected to produce some positive and some negative estimates of variance. The positive and negative between-unit variances in the mean SDs observed across the stages for Peach and EmPower are therefore consistent with no real differences between the units in their measurement of stroke-to-stroke SD. Conversely, the consistency observed in the magnitude of positive variance across the stages is evidence of real differences between Weba units, notwithstanding the uncertainty of the effects. Use of the same Weba unit for repeated measurements of power per stroke would remove any potential error introduced by between-unit differences, although the magnitude of random error added by Weba to stroke-to-stroke measurements of power (as illustrated in Figure 4.7, bottom) is such that Weba is not recommended for the assessment of power per stroke. Some Weba units might also introduce substantial random error into the measurement of mean power in a 2000-m time trial; for example, if the SD of power per stroke for a unit was 16 %, the error in the mean of ~256 strokes in the trial would be $16/\sqrt{256} = 1$ %, which represents substantial error.

4.5.3 Practical applications

4.5.3.1 Peach

- Practitioners should be aware that power output measured by Peach is likely lower than that performed by the rower by ~10 %, but up to ~17 % at maximal power outputs over short (30 s) durations.
- Power measured by Peach is close to that of the Concept2 (within 2 %), but differences of up to 6 % exist between the two devices at power outputs below ~150 W. Differences greater than 2 % in power between Peach and Concept2 observed by practitioners therefore likely reflect differences in the application of power relating to the increased technical demand in on-water rowing.
- The technical error of measurement (TEM) for Peach was ~5 % which represents large to very large errors being introduced between sessions. Negligible session-to-session reliability is represented by TEM values of <0.5 %.
- Peach can be used with confidence for assessments of stroke-to-stroke power and of relationships between power and rowing performance, given its negligible lack of measurement sensitivity (~-6 % difference from the Reference System in the mean SD of power, and up to 16 % at maximal efforts over 30 s).

4.5.3.2 EmPower

- Practitioners should be aware that power measured with EmPower devices may be substantially lower (~25 %) than when measured with Peach, Weba, or Concept2 devices. It is therefore advisable that practitioners use the same device when comparing measures of power output, particularly when using EmPower.
- The technical error of measurement (TEM) for EmPower was ~18 % which represents extremely large errors being introduced between sessions. Negligible session-to-session reliability is represented by TEM values of <0.5 %.
- EmPower is best used to assess mean power rather than power per stroke owing to the noise in its signal output, which was represented by random error estimates of ~15 % and up to 57 % at maximal efforts over 30 s. Negligible random error magnitudes are <11 % for stroke-to-stroke measures of power.

4.5.3.3 Weba

- Practitioners should be aware that power output measured by Weba is likely lower than that performed by the rower by ~10 %, but is similar (within ~5 %) to that of Peach and the Concept2.
- The technical error of measurement (TEM) for Weba was ~10 % which represents extremely large errors being introduced between sessions. Negligible session-to-session reliability is represented by TEM values of <0.5 %.
- Weba is best used to assess mean power rather than power per stroke owing to the noise in its signal output, which was represented by random error estimates of 61-139 %. Negligible random error magnitudes are <11 % for stroke-to-stroke measures of power.

4.5.3.4 Concept2

- Practitioners should be aware that power output measured by Concept2 is likely lower than that performed by the rower by ~10 %, but is similar (within ~5 %) to that of Peach and Weba.
- The technical error of measurement (TEM) for Concept2 was ~1.5 % and was lower than that for Peach, Weba, and EmPower. Negligible session-to-session reliability is

represented by TEM values of <0.5 %, nonetheless the magnitude of error introduced by the Concept2 between sessions is only small.

- Concept2 measurement sensitivity for the assessment of stroke-to-stroke power is ~20 % lower in comparison to the Reference System. When assessing stroke-to-stroke power practitioners should exclude the first ~5 strokes or use tests involving rolling starts to account for the greater negative offset in power associated with stationary starts on the Concept2.

4.6 Conclusion

Mean power was found to be lower in comparison to the Reference System for all devices. Magnitudes of negative systematic error were similar for Peach, Weba, and the Concept2, but larger for EmPower. Stroke-to-stroke variations in power were consistent between Peach and the Reference System, but a small reduction in measurement sensitivity was evident for the Concept2, whereas EmPower and Weba introduced noise. There was some evidence of between-unit differences in mean power for Peach, EmPower, and Weba, and in the SD of power (stroke-to-stroke fluctuations) for Weba. The findings of this study can be used by practitioners to inform the interpretation of meaningful change in measures of power when using the devices.

Chapter Five: Prediction of 2000-m On-Water Rowing Performance with Measures Derived from Instrumented Boats

5.1 Abstract

Purpose: Rowing instrumentation systems provide measures of stroke power, stroke rate and boat velocity during rowing races, but how well these measures predict race performance has not been reported previously. **Methods:** Data was collected per stroke from 45 2000-m races using Peach PowerLine and OptimEye S5 GPS units. The boat classes assessed were nine male singles, eight female singles, three male pairs, and six female pairs. Random effects and residuals from general linear mixed modelling of stroke velocity adjusted for stroke power, stroke rate, and mean headwind provided measures interpreted as technical efficiency, race conditions, and stroke-velocity variability. These measures, along with mean race power, mean stroke rate, and mean headwind were then included in multiple linear regressions to predict race velocity from official race times. Effects were assessed for 2-SD changes in predictors and interpreted using interval-hypothesis tests. **Results:** Effects of mean race power, mean stroke rate and mean headwind on race velocity ranged from small to extremely large and were mostly decisively substantial. Effects of technical efficiency and race conditions ranged from trivial to extremely large but were generally unclear, while stroke-velocity variability had trivial-small and mostly unclear effects. Prediction error was small to moderate and decisively substantial. Men's pairs lacked sufficient data for analysis. **Conclusion:** On-water rowing race performance can be predicted with race mean values of power, stroke rate and headwind. Estimates from stroke data are potentially useful predictors but require impractical numbers of boats and races to reduce their uncertainty.

5.2 Introduction

The prediction of race performance is a valuable tool, providing clarity on what separates an athlete's current performance from the desired performance outcome. Prediction models assess the contribution of measures to overall race performance, therefore increasing the understanding of performance demands. Prediction models also enable the estimation of the power required to achieve a specific race performance, and the identification of athlete-specific areas where performance can be improved (Faria et al., 2005; Schumacher & Mueller, 2002b). Performance prediction models have been used in other sports such as road cycling to accurately predict performance (J. C. Martin et al., 1998), which holds promise for successful performance prediction in sports where environmental conditions vary, such as on-water rowing.

On-water rowing velocity has been successfully modelled from simulations of blade movement through the water (Caplan & Gardner, 2007a), and body-segment kinematics during ergometer rowing (Caplan & Gardner, 2007b). However, an analysis of on-water assessment of power, rower synchronization, and rower drag contribution in men's coxless pairs did not successfully predict rowing velocity (Baudouin & Hawkins, 2004). Studies investigating the factors influencing on-water rowing performance have identified relationships with rowing performance for on-water power output per stroke (r = 0.44-0.67) (Coker, 2010), stroke rate (Kleshnev, 2001; T. P. Martin & Bernfield, 1980), 2000 m ergometer performance (r = 0.55-0.92 for small boat classes) (Mikulić, Smoljanovic, Bojanic, Hannafin, & Matković, 2009; Mikulić, Smoljanović, Bojanić, Hannafin, & Matković, 2009), maximal aerobic power (r = 0.63), 30 s mean maximal power (r = 0.60), and lower limb strength (r = 0.54) (Otter-Kaufmann et al., 2019). The effect of different measures of rowing technique on boat velocity (Coker, 2010), and differences in measures of rowing technique between rowers of varying success levels have been assessed (Kleshnev, 2010a; R. M. Smith & Draper, 2006; Warmenhoven, Cobley, et al., 2017), but the overall contribution of rowing technique to on-water performance is not yet known. Additional studies have investigated determinants of 2000 m rowing ergometer performance, where the assessment of physiological variables can be undertaken in a controlled environment. Large relationships have been found with 2000 m ergometer rowing performance for maximal oxygen uptake ($L \cdot min^{-1}$; r = 0.50-0.92) (Bourdin et al., 2017; Ingham et al., 2002; Kendall et al., 2011; Riechman et al., 2002), power at the second lactate threshold (r = 0.55-0.88) (Ingham et al., 2002; Kendall et al., 2011), and peak power (r = 0.85-0.95) (Ingham et al., 2002; Riechman et al., 2002), but the translation of these findings to on-water rowing performance has not been reported.

The prediction of performance in rowing from on-water measures is evidently difficult, likely related to the technical demands and variability of environmental conditions in rowing. Progress towards the accurate prediction of rowing performance might be possible with use of kinetic data for each stroke available from the instrumentation of boats. Therefore, the aim of this study was to determine how well 2000-m on-water rowing race performance can be predicted with measures derived from kinetic data, including mean race power and stroke rate. Analysis of multiple races and the inclusion of headwind also provided measures of rowing technique (technical efficiency) and race conditions, which were included as predictors of race performance.

5.3 Methods

5.3.1 Participants

Sixteen female (age 20.7 ± 2.4 y; height 177.2 ± 6.3 cm; body mass 73.6 ± 7.8 kg, mean ± SD) and fourteen male (age 21.6 ± 2.8 y; height 189.3 ± 8.1 cm; body mass 84.8 ± 10.4 kg) well-trained, National and International-level rowers volunteered for this study. Participants provided informed consent prior to commencement of the study. The study was approved by the University ethics committee and conforms to the Code of Ethics of the World Medical Association.

5.3.2 Study design

The study was conducted during two national regattas held at the Sydney International Regatta Centre, Australia. 45 2000-m races were recorded from 9 male single scull crews (16 races), 8 female single scull crews (13 races), 3 male coxless pair crews (5 races), and 6 female coxless pair crews (11 races). Races recorded were heats (18 races), repecharges (3 races), semi-finals (3 races) and finals (21 races). Crew age categories were <21 y (2 crews), <23 y (19 crews), and Senior (>22 y; 5 crews). There were not enough races in each race type and crew age category to analyse these variables separately, but this information is included for completeness of the methods. Crews were given no instructions from the researchers regarding race strategy or stroke rate.

5.3.3 Equipment and data analysis

Peach PowerLine instrumentation systems (Peach; Peach Innovations, UK) were attached to participants' boats to collect power and stroke rate per stroke during races. The additional ~1 kg for single and pair boat classes that Peach adds is not expected to influence rowing performance. Peach calculates power from force measured at the oarloack and oarlock angle collected with a 50 Hz sample rate. Stroke rate is calculated from the time period between consecutive strokes, delineated by the drive start (the first occurrence of oarlock force exceeding a threshold value at the start of the drive (propulsive) phase of the stroke). Calibration of Peach force and gate angle was conducted immediately prior to each race, following manufacturer's instructions. In Chapter Four Peach was shown to have acceptable validity for assessments of stroke-to-stroke power over power outputs and stroke rates ranging from ~100-500 W and 18-44 strokes·min^{-1} in comparison to the Reference System in the simulation of on-water rowing, where negligible random error estimates of ~-6% (trivial random errors for power in rowing are -10 to 11%) were observed, which relates to a negligible attenuation of effects with power as a predictor of rowing performance. Power and stroke rate per stroke were exported from the Peach PowerLine software to an Excel spreadsheet where they were aligned with boat velocity, wind speed and wind direction data by stroke number. Mean race power and mean stroke rate were calculated from the values for power and stroke rate per stroke throughout each race.

OptimEye S5 GPS units (Catapult, Australia) attached to the stern canvas of participant boats approximately 10 cm from the footwell and collected boat velocity and acceleration with 10 and 100 Hz sample rates, respectively. Acceptable levels of validity have been established for measures of rowing velocity from Catapult GPS units (~0.1% standard error of the estimate [SEE], where trivial changes in rowing velocity are <0.3 %) (T. B. Smith & Hopkins, 2012), however the validity of rowing velocity measures from Optimeye S5 units has not been assessed in peer-reviewed research. The software Logan (version 48.41, Catapult, Australia) was used to combine Peach and GPS race data by aligning the acceleration traces from each device. Boat velocity per stroke was then derived from the GPS data with strokes partitioned from catch-to-catch, with the catch identified as the largest negative oarlock angle achieved per stroke. Boat velocity per stroke was then exported from Logan into an Excel spreadsheet.

Race times were obtained from published official race times, collected using the FinishLynx automatic timing system (Brook Group, Australia), from which race velocities were calculated. The FinishLynx automatic timing system is a FISA-standard timing system and has a frame rate of 1000 Hz. Venue environmental conditions (collected at 1-min intervals from six weather stations positioned at water level along the 2000 m course) were 23.5 ± 3.2 °C air temperature (mean ± SD), 26.6 ± 2.1 °C water temperature, and 58 ± 17 % relative humidity. Wind velocity was interpolated to provide a value for each stroke, resolved as a headwind, and averaged over each race (Table 5.1).

5.3.3 Statistical analysis

Each boat class was analysed separately with the general linear mixed-model procedure (Proc Mixed) in the Studio University edition of the Statistical Analysis System (version 9.4, SAS Institute, Cary NC). The logarithm of stroke velocity (V) was the dependent. There were three fixed effects: the logarithm of mean stroke power (P) of both oars (added), allowing estimation of the coefficient of log(stroke power) (the exponent x in the kinetic equation $V = k \cdot P^x$); the logarithm of stroke rate, allowing estimation of its contribution as a coefficient; and a linear numeric effect for mean race headwind. Random effects were: crew identity (representing consistently better or worse technical efficiency of each crew across races); crew identity interacted with log(stroke power) and log(stroke rate) (representing individual differences between crews in the exponents); race identity (representing race conditions, consisting of between-race changes in mean velocity due to changes in environmental conditions and the efficiency of the crew), and a different residual error for each race (representing stroke-to-stroke variability in velocity within races).

Multiple linear regressions (with Proc Mixed) for singles and women’s pairs were then performed to assess the contributions of mean race power, mean stroke rate, technical efficiency, mean headwind, race conditions, and stroke-velocity variability to race velocity. Multiple linear regressions could not be performed for men’s pairs due to insufficient data (only five races were recorded, which would not allow the assessment of six predictors). Technical efficiency and race conditions were the random-effect solutions for crew identity and race identity respectively from the previous mixed model, and stroke-velocity variability was the residual SD for each race from that model. Effects of each predictor on race velocity were assessed for a two standard-deviation (2SD) between-race change (for mean race power, mean stroke rate, and race conditions), a 2SD between-crew difference (for technical efficiency), and a 2SD within-race change (for stroke-velocity variability) by multiplying the regression coefficient by 2SD (Hopkins et al., 2009); the effect of headwind was assessed for a 2-$m \cdot s^{-1}$ increase (approximately 2SD between-race change). It was apparent that most of the uncertainty in the effects of mean race power and stroke-velocity variability came from their respective regression coefficients; their uncertainties and reference-Bayesian likelihoods of substantial or trivial effects (see below) are therefore shown accordingly, whereas the uncertainties and reference-Bayesian likelihoods for the SD representing technical efficiency and race power were provided by the stroke-velocity analysis. Bootstrapping could in principle provide estimates of the sampling uncertainty in these effects arising from uncertainty in the SD and the regression coefficients, but thousands of repetitions of the mixed model would take a prohibitive period of time, and the low numbers of crews and races would compromise the bootstrapped estimates. The residual error for the multiple linear regression represented the remaining unexplained prediction error of race velocity with mean race power, mean stroke rate, technical efficiency, and race conditions as predictors; uncertainty and reference-Bayesian likelihoods of substantial or trivial effects for this error were provided accurately by the multiple linear regression.

A smallest important change in velocity of 0.3% was chosen, as estimated by Smith and Hopkins (T. B. Smith & Hopkins, 2011) from the 1.0% race-to-race variation in 2000-m race times of elite rowers. Corresponding magnitude thresholds for differences or changes in velocity were: <0.3% trivial, ≥0.3% small, ≥0.9% moderate, ≥1.6% large, ≥2.5% very large, and ≥4.1% extremely large (Hopkins et al., 2009). The above magnitude thresholds are halved when evaluating SD to allow the magnitude of the SD to be evaluated as the difference between typically low and high values. However, to evaluate magnitudes of the SD representing between-crew differences in technical efficiency and within-crew changes in race conditions in the initial analyses (Figure 5.1 and Supplementary Table 1), the SD were doubled (T. B. Smith & Hopkins, 2011). To evaluate the magnitude of the residual prediction error in the multiple linear regression, the magnitude thresholds were one-half of those in the above scales (T. B. Smith & Hopkins, 2011).

Sampling uncertainty in effects and SD is shown as 90% compatibility limits (90%CL), derived by assuming a normal distribution (t for effects, z for random-effect SDs squared, and chi-squared for residual variances; 90%CL for SD are shown in approximate ± form and in approximate ×/÷ form for residuals). Decisions about magnitudes accounting for the uncertainty were based on one-sided interval hypothesis tests, according to which an hypothesis of a given magnitude (substantial, non-substantial) is rejected if the 90% compatibility interval falls outside that magnitude. P values for the tests were therefore the areas of the sampling distribution of the effect falling in the hypothesized magnitude, with the distribution centered on the observed effect. Hypotheses of inferiority (substantial negative) and superiority (substantial positive) were rejected if their respective p values ($p_{–}$ and p_{+}) were <0.05. When only one hypothesis was rejected, the p value for the other hypothesis, when >0.25, was interpreted as the posterior probability of a substantial true magnitude of the effect in a reference-Bayesian analysis with a minimally informative prior (Hopkins, 2019) using the following scale: >0.25, possibly; >0.75, likely; >0.95, very likely; >0.995, most likely (Hopkins et al., 2009); the probability of a trivial true magnitude ($1 – p_{–} – p_{+}$) was also interpreted, when >0.25, with the same scale. Probabilities were not interpreted for effects that were unclear (those with inadequate precision at the 90% level, defined by failure to reject both hypotheses, $p_{–}$ >0.05 and p_{+}>0.05). Effects with adequate precision at the 99% level ($p_{–}$<0.005 or p_{+}<0.005) are shown in bold, since these represent effects that have a conservative low risk of harm (most unlikely to impair performance, if implemented). The hypothesis of non-inferiority (non-substantial-negative) or non-superiority (non-substantial-positive) was rejected if its p value ($p_{N–} = 1 – p_{–}$ or $p_{N+} = 1 – p_{+}$) was <0.05, representing a decisively substantial effect in minimal-effects testing: very likely or most likely substantial.

5.4 Results

Descriptive statistics for the variables predicting race velocity in the multiple linear regression analysis for each boat class are shown in Table 5.1. Technical efficiency and race conditions are random-effect SDs from the initial analysis of stroke data, and therefore have means of zero. Stroke-velocity variability represents the residual SD from the initial analyses.

Table 5.1. Descriptive statistics for race velocity and for predictors of race velocity included in subsequent multiple linear regressions for the four boat classes. Data are mean ± SD.

	Single sculls		Coxless pairs	
	Men (M1x)	Women (W1x)	Men (M2-)	Women (W2-)
Race velocity ($m\cdot s^{-1}$)[a]	4.57 ± 0.10	4.11 ± 0.11	4.93 ± 0.06	4.30 ± 0.14
Mean race power (W)[a]	377 ± 34	225 ± 21	772 ± 38	491 ± 42
Mean stroke rate ($\cdot min^{-1}$)[a]	35.4 ± 1.6	32.7 ± 1.3	38.1 ± 0.7	35.7 ± 2.0
Technical efficiency (%)[b]	0.0 ± 2.5	0.0 ± 0.0	0.0 ± 0.4	0.0 ± 0.9
Mean headwind ($m\cdot s^{-1}$)[a]	-0.3 ± 0.9	-0.1 ± 0.8	-0.2 ± 0.3	0.0 ±1.0
Race conditions (%)[a]	0.0 ± 1.4	0.0 ± 2.1	0.0 ± 0.3	0.0 ± 0.5
Stroke-velocity variability (%)[a]	2.1 ± 0.4	1.8 ± 0.5	1.6 ± 0.2	1.9 ± 0.5

M1x, men’s single scull; W1x, women’s single scull; M2-, men’s coxless pairs; W2- women’s coxless pairs.
[a]Number of races: 16, 13, 5, 11 for M1x, W1x, M2-, W2- respectively.
[b]Number of crews: 9, 8, 3 and 6 for M1x, W1x, M2-, W2- respectively.

The coefficients for stroke power in the initial analysis of stroke data were 0.26 ± 0.04, 0.28 ± 0.05, 0.25 ± 0.08, and 0.30 ± 0.04 $\%\cdot\%^{-1}$ (mean ± SD) for men's singles, women's singles, men's pairs, and women's pairs respectively. The coefficients for stroke rate were respectively 0.22 ± 0.10, 0.17 ± 0.08, 0.34 ± 0.20, and 0.17 ± 0.08 $\%\cdot\%^{-1}$. The coefficients for headwind were respectively -1.19 ± 0.97, -1.91 ± 1.26, -0.63 ± 0.57, -1.01 ± 0.60 $\%/m\cdot s^{-1}$.

Individual values of race velocity, mean race power, mean stroke rate, crew technical efficiency, mean headwind, race conditions and stroke-velocity variability for each race in men’s singles illustrate how similar race velocities were associated with differing contributions of these variables (Table 5.2). For example, Crews A in the heat and Crew B in the final had similar race velocities (differing by 0.02 $m\cdot s^{-1}$ or 0.4%) and stroke rates (0.5 $\cdot min^{-1}$ or 1.4%) but widely differing race power (52 W or 17%) and technical efficiency (-0.8% minus 4.7% or -5.5%). Analysis of race velocity with the other variables as predictors in multiple linear regressions, and similar analyses for the other boat classes, produced the results presented in Table 5.3 and Figure 5.1.

Table 5.2. Individual crew values in men's singles races.

Crew ID	Age-group	Race	Race velocity ($m \cdot s^{-1}$)	Mean race power (W)	Mean stroke rate ($\cdot min^{-1}$)	Technical efficiency (%)	Mean headwind ($m \cdot s^{-1}$)	Race conditions (%)	Stroke- velocity variability (%)
A	Senior	Final	4.76	390	38.7	-0.8	0.2	0.5	1.6
A	Senior	Semi-final	4.71	385	36.7	-0.8	0.5	0.0	2.4
B	U23	Heat	4.68	307	33.6	4.7	-0.5	1.0	2.1
B	U23	Final	4.63	312	34.6	4.7	0.6	-0.1	2.1
A	Senior	Heat	4.61	364	34.1	-0.8	0.0	-0.1	1.9
C	U23	Heat	4.60	304	35.4	1.6	-2.2	-0.1	2.2
C	U23	Final	4.59	310	37.1	1.6	0.4	1.0	1.9
D	U21	Heat	4.58	296	35.0	1.4	-0.5	2.1	2.2
E	U23	Heat	4.57	383	32.0	-1.5	-0.3	-1.3	1.3
F	Senior	Heat	4.57	335	35.0	-0.1	-0.1	1.0	2.0
G	U23	Final	4.56	370	36.8	-1.7	0.4	-0.8	1.9
H	U23	Semi-final	4.49	351	36.4	-2.9	-0.5	-0.7	1.9
I	Senior	Heat	4.46	291	36.9	-0.7	-2.7	-0.4	2.4
H	U23	Final	4.46	340	34.4	-2.9	-0.2	-0.6	2.0
H	U23	Heat	4.43	340	34.5	-2.9	0.0	0.7	2.4
D	U21	Final	4.41	312	36.1	1.4	0.3	-2.2	3.0

Senior, open age category; U23, under 23 years of age; U21, under 21 years of age

The coefficients of the predictors of race velocity in the multiple linear regressions are presented in Table 5.3. The values for mean race power and mean stroke rate are similar in magnitude to their values from the initial analyses of stroke data, given their uncertainties. The uncertainties in technical efficiency and race conditions mostly included their theoretical values of 1.0 $\%\cdot\%^{-1}$. Negative values for stroke-velocity variability would be associated with faster boat velocities, as observed in men's singles but not the other boat classes assessed. There were insufficient data for the estimation of coefficients in the men's pairs.

Table 5.3. Differences or changes in race velocity for a 1% change in predictors (or 1 $m\cdot s^{-1}$ for headwind) that were included in multiple linear regressions in the four boat classes. Data are the coefficients in the regressions ($\%\cdot\%^{-1}$) and ±90%CL.

	Single sculls		Coxless pairs	
Predictor	Men (M1x)	Women (W1x)	Men (M2-)[b]	Women (W2-)
Mean race power	0.27, ±0.03	0.36, ±0.06	—	0.34, ±0.07
Mean stroke rate	0.11, ±0.04	0.11, ±0.10	—	0.14, ±0.19
Technical efficiency	0.98, ±0.11	—[a]	—	1.08, ±0.98
Mean headwind	-1.11, ±0.26	-2.38, ±0.77	—	-1.49, ±1.15
Race conditions	0.92, ±0.19	1.18, ±0.32	—	1.52, ±1.40
Stroke-velocity variability	-0.25, ±0.61	0.65, ±1.35	—	0.23, ±1.25

M1x, men's single scull; W1x, women's single scull; M2-, men's coxless pairs; W2- women's coxless pairs.
Number of crews and races are shown in Table 5.1.
[a]No coefficient estimated due to negative variance in the random effect for this variable (Figure 5.1).
[b]Insufficient data for analysis in men's pairs (five races for six predictors).

To assess their contribution to race performance, the coefficients in Table 5.3 were multiplied by 2 SD of their respective predictors, and are presented in Figure 5.1 and in Supplementary Table 1 with $p_{–}$ and p_{+} values and reference-Bayesian likelihoods of substantial and trivial effects. Extremely large positive effects on mean race velocity that were decisively substantial (rejection of the non-superiority hypotheses, p_{N+} <0.05) were found for mean race power in all boat classes assessed in the multiple linear regressions.

Effects for mean stroke rate were positive, small to large in magnitude, decisively substantial in men's singles and possibly substantial in women's singles (rejection of only the inferiority hypothesis, $p_{-} < 0.05$). Effects for technical efficiency and race conditions are from the initial analyses of stroke data. Differences between crews in technical efficiency were trivial to extremely large, but the differences were unclear in all boat classes (the superiority and inferiority hypothesis were not rejected, p_{+} and $p_{-} > 0.05$). Between-race changes in race conditions were extremely large and decisively substantial in women's singles, very large and likely substantial in men's singles (rejection of only the inferiority hypothesis, $p_{-} < 0.05$), and small or moderate but unclear in pairs. The effect of headwind was large to extremely large and decisively substantial in all boat classes. The effect for stroke-velocity variability was possibly trivial, possibly negative in men's singles (rejection of only the superiority hypothesis, $p_{+} < 0.05$), and small to trivial but unclear in the other boat classes.

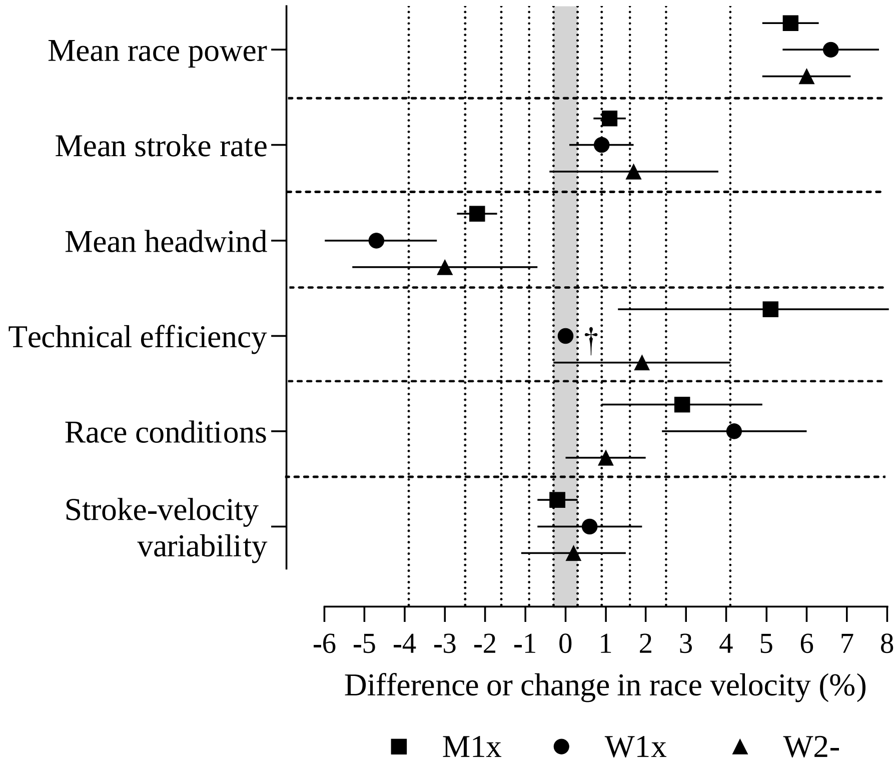

Figure 5.1. Differences or changes in race velocity for a 2-SD change in predictors that were included in multiple linear regressions in the four boat classes. Data are mean (%) for predictors, with ±90% CL. Technical efficiency and race conditions are twice the SDs from the initial analyses of stroke data (Table 5.1). * Indicates negative estimate probably due to sampling variation, so estimated as 0 and therefore no CL; M1x, men's single sculls; W1x, women's single sculls; W2-, women's coxless pairs. The shaded grey area represents values within the smallest important change thresholds (-0.3 to 0.3%). Vertical dotted lines delineate threshold magnitudes of small (±0.3), moderate (±0.9), large (±1.6), very large (±2.5), and extremely large (-3.9, 4.1%). Rejection of the non-inferiority or non-superiority hypothesis occurs when compatibility limits do not enter the grey area. Effects with compatibility limits that end within the grey area have adequate precision but are only possibly or likely substantial or trivial.

Not shown in the tables are the residual errors in the regressions (prediction errors), representing the error associated with the prediction of mean race velocity from measures of mean race power, mean stroke rate, technical efficiency, race conditions, mean headwind, and stroke-velocity variability. The prediction errors were small to moderate in magnitude, and decisively substantial (rejection of the non-superiority hypotheses, p_+ >0.999): 0.37, ×/÷1.50; 0.48, ×/÷1.67; 0.59, ×/÷1.92 % (SD, ×/÷90%CL) for men's singles, women's singles, and women's pairs. There were insufficient data for the estimation of effects in the multiple linear regression analyses for men's pairs.

5.5 Discussion

In this study race performance in rowing was predicted for different boat classes with measures derived from instrumented boats. Although the prediction error was small to moderate, mean race values for power and stroke rate were strong predictors and are therefore areas where substantial improvements in performance can be attained. The predictors coming from the initial analyses of stroke-to-stroke data (technical efficiency and race conditions) may have a meaningful impact on race performance, but there was too much uncertainty in their effects to evaluate their contributions. Error in the measurement of stroke velocity may have contributed to the uncertainty in the effects for technical efficiency and race conditions, as the validity of Optimeye S5 GPS units for measures of stroke velocity in rowing has not been assessed.

The coefficients of the predictors in the initial analyses of stroke data were similar to those in the multiple linear regression given the uncertainties in the estimates in both models, showing that the within-race effects are similar to the between-race effects for power and stroke rate. The coefficients for mean race power (representing the exponent x in the kinetic equation $V = k \cdot P^x$) were somewhat less than the theoretical value of 0.33 $\% \cdot \%^{-1}$ in the analysis of the log-transformed variables, owing to the collinearity of stroke rate and power. The coefficients for headwind reveal a substantial (1-2 % per $m \cdot s^{-1}$ of wind velocity) negative effect on race velocity, which has not been documented in rowing. The coefficients for technical efficiency and race conditions are 1.0 $\% \cdot \%^{-1}$ in the initial analyses of stroke data, because they are random effects, which are purely additive in mixed models. The coefficient for stroke-velocity variability in the multiple linear regression analyses does not have a value for comparison in the initial analyses of stroke data, because the variability is the residual error for each race.

The term technical efficiency describes crew differences from the group mean in the resultant boat velocity for a given power output and stroke rate, where the effects of headwind, race conditions, and stroke-velocity variability (stroke-to-stroke variability in velocity due to technical, environmental, or abrupt pacing changes within a race) are statistically held constant. Crews with negative technical efficiency estimates in Table 5.2 achieve slower boat velocities (in comparison to the group mean for M1x) for the same power and stroke rate, reflecting the effect of their rowing technique on boat velocity. Technical efficiency and race conditions were expected to be important contributors to race performance in the multiple linear regression analyses, representing effects unrelated to power, stroke rate, and headwind. However, the unclear effects and their wide variation in magnitude between boat classes do not permit interpretation of the effect of technical efficiency on velocity from the data, whereby we cannot ascertain the contribution of rowing technique to race performance with confidence in this study.

Assessment of a larger numbers of crews and races would reduce the uncertainty in the effects for technical efficiency. The analysis of race times for all crews (including elites) and all races in the manner of T. B. Smith and Hopkins (2011) combined with mean power and mean stroke rate monitored for a subset of crews might provide an avenue for more successful estimation of the contribution of technical efficiency to performance of those crews with better adjustment for race conditions. Well-defined effects of technical efficiency would lead to better understanding of the aspects of rowing technique responsible for differences in efficiency between crews. In research of relationships between rowing velocity and measures of rowing technique, there were some substantial between-crew individual differences in measures of technique, but the differences were often unclear (Chapter Six). It is important to acknowledge that the measure of technical efficiency in this study is not a direct measure of rowing technique, therefore factors contributing to consistent differences in velocity between crews such as the rower-boat system mass, hull surface area, and oar blade design, may contribute to technical efficiency estimates. Additionally, the estimates for technical efficiency are specific to the mostly National pathway level athletes assessed, whereby between-crew differences in technical efficiency and its effect on race performance would likely be much smaller in a cohort of elite rowers, where the performance standard is higher. These analyses would therefore need to be done using data from an elite cohort to understand the influence of rowing technique on performance in elite rowers.

The between-race effects of power and stroke rate on velocity are supported by findings from the analysis of stroke data within races, where extremely large effects on velocity were established for both power and stroke rate (Chapter Six). Additionally, strong correlations have been established with velocity for power ($r = 0.44$-0.67) (Coker, 2010) and stroke rate ($r \geq 0.66$) elsewhere (Kleshnev, 2001; T. P. Martin & Bernfield, 1980). Therefore, the positive effects for mean race power and mean stroke rate in Figure 5.1 highlight these variables as key areas where substantial improvements in rowing race performance can be achieved. Furthermore, strong positive relationships exist between stroke rate and power (Held, Siebert, & Donath, 2020; Hofmijster et al., 2007), whereby increases in stroke rate contribute to increases in power for the same applied force, due to the decrease in stroke time over which power is calculated. Hence, a rower attempting to improve race performance by increasing stroke rate would likely also increase power, and both would contribute to enhancement of performance, given the model predicts additive effects of these variables.

The contributions of technical efficiency, mean stroke rate, and mean race power to performance can vary widely between crews, as demonstrated in Table 5.2, and when assessed individually will inform areas for performance improvement. The inclusion of age group in Table 5.2 shows younger rowers to typically have lower mean race power values, as can be expected. Technical efficiency does not appear to be related to age group in the cohort assessed, suggesting improvements in technical efficiency may be difficult to attain.

The SD for race conditions in Table 5.1 represent between-race changes in velocity due to environmental conditions. This SD is derived after adjustment for power, so it includes any changes in crew performance that are unrelated to power (e.g., rowers having worse or better technical efficiency than usual in a given race due to differences in crew synchronicity) (Hill, 2002). The SD are smaller than the ~3.0% SD between-final and between-venue variability of race times in elite crews attributed to the effect of environmental conditions (T. B. Smith & Hopkins, 2011), likely due to a more diverse sample of races and venues assessed previously, and the inclusion of headwind as a predictor in the current study. The trend for smaller SD observed in pairs than singles in the current study (Figure 5.1 and Supplementary Table 1) corresponds with the 20% smaller SD observed in pairs compared to singles in elite racing (T. B. Smith & Hopkins, 2011), supporting the interpretation of adverse environmental conditions having a greater effect on smaller boat classes (T. B. Smith & Hopkins, 2011).

Although the contributions of headwind and other race conditions to race performance were substantial in the current study, performance can be predicted from mean race power, mean stroke rate, and technical efficiency alone. Where the effects of environmental conditions on performance in a given race impact all crews in that race equally, the estimation of race performance without the inclusion of race conditions would still predict the performance outcome. As such, the coefficients in the multiple linear regression can be used to estimate the power, stroke rate, and technical efficiency required for a given crew to achieve a benchmark race time, provided their technical efficiency has been estimated using stroke data from a cohort of rowers of a similar level. Estimation of individual differences in the effect of headwind between crews from the inclusion of a random effect for headwind interacted with the crew identity would allow for a more precise prediction of a given crew's race performance in a given headwind or tailwind. However, estimation of individual differences for headwind would require data from more races than were available in the present study.

5.5.1 Practical Applications

- 2000-m on-water rowing performance can be estimated with less than 0.6% error from measures derived from instrumented boats in singles and coxless pairs.
- Of the variables assessed, power output has the greatest modifying effect on on-water rowing performance.
- Stroke rate is another area where substantial performance improvements can be made.
- Contributions of power, stroke rate, and technical efficiency to performance differ between crews and inform areas for performance improvement when assessed individually.

5.6 Conclusion

Power output, stroke rate and measures of rowing technique have been shown to be important factors in on-water rowing performance, but the prediction of on-water race performance had not been investigated using data derived from these measures. This study estimated 2000-m on-water rowing performance with less than 0.6% error from measures of power output, stroke rate, technical efficiency, headwind, race conditions, and stroke-velocity variability in singles and coxless pairs. Of the variables assessed, power output had the greatest modifying effect on on-water rowing performance, with stroke rate demonstrating an additional area where substantial performance improvements can be achieved. Technical efficiency may have a meaningful impact on performance but requires further investigation. The differing contributions of power, stroke rate, and technical efficiency to performance between crews can be used to inform areas for performance improvement when assessed individually.

Chapter Six: Technical Determinants of On-Water Rowing Performance

6.1 Abstract

Purpose: Research establishing relationships between measures of rowing technique and velocity is limited. In this study measures of technique and their effect on rowing velocity were investigated. **Methods:** Ten male singles, eight female singles, three male pairs, and six female pairs participated. Data from each stroke for 47 2000-m races were collected using Peach PowerLine and OptimEye S5 GNSS units. General linear mixed modelling established modifying effects on velocity of two within-crew SD of predictor variables for each boat class, with subsequent adjustment for power, and for power and stroke rate in separate analyses. Twenty-two predictor variables were analysed, including measures of boat velocity, gate force, and gate angle. Results were interpreted using superiority and inferiority testing with a smallest important change in velocity of 0.3%. **Results:** Substantial relationships with velocity were found between most variables assessed before adjustment for power, and for power and stroke rate. Effect magnitudes were reduced for most variables after adjustment for power, and further reduced after adjustment for stroke rate and power, with precision becoming inadequate in many effects. The greatest modifying effects were found for stroke rate, mean and peak force, and power output before adjustment, and for catch angle after adjustment for stroke rate and power. Substantial between-crew differences in effects were evident for most predictors in some boat classes before adjustment and in some predictors and some boat classes after adjustment for stroke rate and power. **Conclusion:** The results presented reveal variables associated with improvements in rowing performance and can be used to guide technical analysis and feedback by practitioners. Higher stroke rates and greater catch angles should be targeted to improve rowing performance, and rower force development for the improvement of power output. Relationships between rowing technique and velocity can be crew-dependent and are best assessed on an individual basis for some variables.

6.2 Introduction

Rowing is a sport with high technical demand, whereby an athlete's on-water performance ability is a product not only of their physiological work capacity but also their technical ability. With the use of instrumentation systems, practitioners have the means for quantitative assessment of multiple variables associated with rowing technique, allowing feedback to coaches and athletes regarding beneficial areas of technical focus. Key areas for technical assessment include the oar angle rowed through (arc angle) and the application of force to the oar, as these measures contribute to propulsive work (Warmenhoven et al., 2018). Longer arc angles achieved through more negative catch and more positive finish angles, and smaller catch and finish slips are often sought by coaches. However, contradictory findings regarding the direction of relationships between these variables and boat velocity have been observed (Coker, 2010). The effect of oar angle achievement on velocity has not been compared between boat classes and genders, although, larger arc angles are achievable in sculling (two oars per rower) than sweep rowing (one oar per rower), and smaller arc angles have been reported in females compared to males (Coker, 2010; Kleshnev, 1998). Arc angle is also related to stroke rate, as arc angles decrease through reductions occurring predominantly to catch angle with increases in stroke rate above 24 strokes·min^{-1} (Kleshnev, 2007).

Power output is commonly assessed by practitioners, and has moderate to large relationships with velocity in scullers (Coker, 2010). Strong positive relationships also exist between power and stroke rate (Held et al., 2020; Hofmijster et al., 2007). The rate of force development and the occurrence of peak force at more negative oar angles are associated with more successful scullers (Warmenhoven, Cobley, et al., 2017). Larger mean-to-peak force ratios (representing more consistent force application) exist in elite men's pairs compared to sub-elite pairs (R. M. Smith & Draper, 2006). Similarly, higher peak and mean forces, with more negative peak force oar angles have been reported for senior compared to underage rowers (Kleshnev, 1998), likely related to increased force development capacity with age. However, how these relationships differ between boat classes and genders has not yet been examined.

Research investigating relationships between measures of rowing technique and performance is valuable for informing technical analysis and athlete feedback. However, further investigation to determine the direction of relationships with boat velocity where findings are contradictory, and to explore differences between boat classes and genders in relationships between technical measures and velocity is needed as these are rarely compared. Furthermore, the investigation of associations between additional measures of rowing technique and boat velocity that have not yet been assessed, is warranted. Therefore, the purpose of this study was to investigate the separate effects of multiple measures of rowing technique on boat velocity in men's and women's singles and coxless pairs during 2000-m racing. The outcomes of this study will advise which technical measures have the greatest associations with rowing performance, informing practitioner assessment and feedback regarding rowing technique.

6.3 Methods

6.3.1 Subjects

Seventeen female (age 20.7 ± 2.4 y; height 177.2 ± 6.3 cm; body mass 73.6 ± 7.8 kg) and fourteen male (age 21.6 ± 2.8 y; height 189.3 ± 8.1 cm; body mass 84.8 ± 10.4 kg) National-pathway rowers who performed regular training volumes of approximately 17-22 $h \cdot wk^{-1}$ volunteered for this study. Participants provided informed consent prior to commencement of the study. The study was approved by the University ethics committee and conforms to the Code of Ethics of the World Medical Association.

6.3.2 Study design

The study was conducted during two national regattas held at the Sydney International Rowing Centre. A total of 47 2000-m races were recorded from ten male single scull crews (seventeen races), eight female single scull crews (thirteen races), three male coxless pair crews (five races), and six female coxless pair crews (twelve races). Crew age categories were <21 y (three crews), <23 y (eighteen crews), and Senior (>22 y; five crews). Races recorded were heats (twenty races), repêcharges (three races), semi-finals (three races) and finals (twenty-one races). Crews were given no instructions from the researchers regarding race strategy or stroke rate. Power output and predictor variables were collected per stroke from races using Peach PowerLine instrumentation systems (Peach Innovations, UK) with a 50 Hz sample rate. Boat velocity and acceleration was collected with a 100 Hz sample rate from OptimEye S5 GNSS units (Catapult, Australia) attached to participant boats. Both Peach PowerLine instrumentation and Catapult GNSS systems are used frequently within elite rowing programs. Acceptable levels of validity have been established for measures of rowing velocity from Catapult GNSS units (T. B. Smith & Hopkins, 2012), and for force and oar angle by Peach instrumentation systems (Coker et al., 2009). Power provided by the Peach instrumentation system represents a proxy measure of the true mechanical power output (Hofmijster et al., 2018). Venue environmental conditions (collected at 1-min intervals from six weather stations positioned at water level along the 2000 m course) were: 22.8 ± 2.1 °C air temperature (mean ± SD); 26.0 ± 1.3 °C water temperature; 59.0 ± 10.3 % relative humidity; and 1.4 ± 0.6 $m \cdot s^{-1}$ wind speed, in a predominantly cross-tail direction on stroke side.

The predictor variables assessed were measures available from the combination of Peach and GNSS data, and most were common variables used by coaches and sport scientists in technical analysis. Peach and OptimEye S5 race data were combined using the software Logan (version 48.41, Catapult, Australia) to align acceleration traces from each device. Strokes were partitioned from catch-to-catch, with the catch identified as the largest negative gate angle, the finish as the largest positive gate angle achieved during one stroke-cycle, and arc angle as the absolute difference in gate angle between catch and finish angles per stroke. The drive was defined as the period between the catch and the subsequent finish, and the recovery as the period between the finish and the catch of the subsequent stroke. Most predictor variables presented in Table 6.1 were calculated per stroke using Logan and exported for statistical analysis. Power output (W; as measured by Peach from gate angle velocity, gate force in the direction of the boat's long axis, and the oar outboard (distance from the collar to blade tip)-to-total length ratio), peak force angle (°; the gate angle during the drive where peak force occurs), catch and finish slip per stroke were exported from PowerLine (version 4.02, Peach Innovations, UK). Catch and finish slips were defined as the gate angles rowed through at the catch and finish respectively, where gate force was below the standard force thresholds of 196 N (catch slip) and 98 N (finish slip) (Coker, 2010). Predictor variables exported from Logan include stroke rate ($stroke \cdot min^{-1}$), within-stroke velocity range ($m \cdot s^{-1}$; difference between maximum and minimum boat velocities occurring within each stroke), time from catch to minimum velocity (s; duration from catch to minimum boat velocity occurring in the early drive), distance per stroke (m), mean force (N; mean force measured at the gate during the drive), peak force (N; highest force measured at the gate during the drive), rate of force development ($N \cdot s^{-1}$; change in force over change in time between the catch and peak force occurrence during the early-to-mid drive), time to peak force from the catch (s; duration from the catch to the occurrence of peak force during the drive), mean-to-peak force ratio (calculated as peak force divided by mean force). The first ten strokes of each race were excluded from analyses to remove outliers, with remaining strokes from each race assessed.

6.3.3 Statistical Analysis

Each gender and boat class were analysed separately with the general linear mixed-model procedure (Proc Mixed) in the Studio University edition of the Statistical Analysis System (version 9.4, SAS Institute, Cary NC). The fixed effects in the model, predicting the logarithm of boat velocity (V), were each predictor variable presented in Table 6.1 analysed separately as linear predictors, allowing estimation of the mean modifying effect on velocity of two within-crew standard deviations (one above and one below the adjusted mean of zero). Separate analyses were conducted to adjust for power output, and to adjust for power output and stroke rate; in these analyses log(V) was predicted by the logarithm of the sum of mean stroke power (P) of both oars, allowing estimation of k and x in the kinetic equation $V = k \cdot P^x$, where the exponent x was allowed to vary between crews, to adjust for individual differences in its value. Fixed effects in the model were log(P) and log(stroke rate) (adjusting log(V) for power output and stroke rate), and each predictor variable separately as linear predictors. Effects on boat velocity were assessed over a two standard deviation (SD) within-crew change in each predictor (Hopkins et al., 2009). The modifying effects of gate force and gate angle variables on velocity were estimated for the bow and stroke side; similar effects were generally observed for both sides so the summed effect of the sides is presented for force measures, and the mean effect of the sides presented for angle and time measures.

Random effects in the model were: crew identity (to adjust for consistently better or worse velocity of each crew across all races); the given predictor variable (for bow and stroke side, where relevant) interacted with crew identity (to estimate individual differences between crews in the effect of the variable); race identity (to adjust for between-race changes in mean velocity due to changes in environmental conditions and the efficiency of the crew); and a different residual error for each crew (representing stroke-to-stroke variability in velocity not accounted for by the other effects). The random effects for the stroke and bow side variables were combined by summing their variances for force measures, and taking their mean variance for angle and time measures, on the assumption that they acted independently. The random effects for crew identity and race identity represent adjustments to improve precision and therefore do not contribute directly to the effects of technique variables on boat velocity; these effects will be reported elsewhere.

A smallest important change in velocity of 0.3% was assumed, given the 1.0% race-to-race variation in 2000-m race times of elite rowers (T. B. Smith & Hopkins, 2011). Corresponding magnitude thresholds for changes in velocity were: <0.3% trivial, ≥0.3% small, ≥0.9% moderate, ≥1.6% large, ≥2.5% very large, and ≥4.1% extremely large (Hopkins et al., 2009). To evaluate magnitudes of standard deviations representing between-crew differences in the modifying effect of each predictor variable on boat velocity, the square of the standard deviation was assumed to be normally distributed and the magnitude thresholds are one-half of those in the above scales, equivalent to evaluating two standard deviations with the above thresholds: <0.15% trivial, ≥0.15% small, ≥0.45% moderate, ≥0.8% large, ≥1.3% very large, and ≥2.0% extremely large (T. B. Smith & Hopkins, 2011).

Sampling uncertainty in the estimates of effects is presented as 90% compatibility limits. Decisions about magnitudes accounting for the uncertainty were based on one-sided interval hypothesis tests, according to which an hypothesis of a given magnitude (substantial, non-substantial) is rejected if the 90% compatibility interval falls outside that magnitude (Aisbett et al., 2020; Hopkins, 2020). P values for the tests were therefore the areas of the sampling distribution of the effect (t for means, z for variances) falling in the hypothesized magnitude, with the distribution centered on the observed effect. Hypotheses of inferiority (substantial negative) and superiority (substantial positive) were rejected if their respective p values (p_- and p_+) were <0.05; rejection of both hypotheses represents a decisively trivial effect in equivalence testing. When only one hypothesis was rejected, the p value for the other hypothesis, when >0.25, was interpreted as the posterior probability of a substantial true magnitude of the effect in a reference-Bayesian analysis with a minimally informative prior (Hopkins, 2019) using the following scale: >0.25, possibly; >0.75, likely; >0.95, very likely; >0.995, most likely (Hopkins et al., 2009); the probability of a trivial true magnitude ($1 - p_- - p_+$) was also interpreted, when >0.25, with the same scale, which should help researchers and practitioners to understand the uncertainty in the effects. Probabilities were not interpreted for effects that were unclear (those with inadequate precision at the 90% level, defined by failure to reject both hypotheses, $p_{–}$>0.05 and p_{+}>0.05). Effects with adequate precision at the 99% level ($p_{–}$ <0.005 or p_{+}<0.005) are shown in bold in tables, since these represent effects that have a conservative low risk of harm (most unlikely to impair performance), if implemented. The hypothesis of non-inferiority (non-substantial-negative) or non-superiority (non-substantial-positive) was rejected if its p value ($p_{N–} = 1 – p_{–}$ or $p_{N+} = 1 – p_{+}$) was <0.05, representing a decisively substantial effect in minimal-effects testing: very likely or most likely substantial.

6.4 Results

Mean values for predictor variables with between-crew and within-crew SD are presented in Table 6.1. Within-crew SD indicate half of the range that effects for predictors were assessed over. The mean modifying effects of predictor variables on boat velocity are presented in Figure 6.1 for all four boat classes, and in Supplementary Table 2 with $p_{–}$ and p_{+} values and reference-Bayesian likelihoods of substantial and trivial effects.

Table 6.1. Characteristics of the predictor variables in the four boat classes. Data are mean ± between-crew SD/within-crew SD[a].

	Single sculls		Coxless pairs	
	M1x	W1x	M2-	W2-
Time and boat-velocity variables				
Stroke rate (strokes·min^{-1})	34.7 ± 1.7/2.0	32.8 ± 1.0/1.8	38.1 ± 0.7/1.7	35.1 ± 2.0/2.3
Within-stroke velocity range (m·s^{-1})	2.27 ± 0.20/0.13	2.14 ± 0.12/0.12	2.71 ± 0.11/0.12	2.30 ± 0.12/0.14
Time from catch to minimum velocity (s)	0.14 ± 0.03/0.04	0.12 ± 0.04/0.02	0.13 ± 0.00/0.01	0.15 ± 0.01/0.03
Distance per stroke (m)	7.97 ± 0.43/0.33	7.65 ± 0.18/0.29	7.82 ± 0.19/0.17	7.38 ± 0.34/0.28
Gate force variables				
Mean force (N)	261 ± 26/21	199 ± 17/16	503 ± 40/40	367 ± 34/38
Power output (W)	334 ± 33/34	223 ± 21/25	760 ± 38/92	481 ± 43/58
Peak force (N)	497 ± 68/34	371 ± 48/30	968 ± 81/65	694 ± 97/68
Rate of force development (N·s^{-1})	960 ± 190/100	760 ± 270/190	1980 ± 240/190	1450 ± 270/200
Time to peak force from the catch (s)	0.43 ± 0.07/0.04	0.39 ± 0.04/0.04	0.36 ± 0.03/0.03	0.36 ± 0.07/0.05
Mean-to-peak force ratio	1.90 ± 0.13/0.08	1.87 ± 0.13/0.06	1.88 ± 0.16/0.06	1.89 ± 0.13/0.08
Peak force angle (°)	-20.1 ± 5.2/4.0	-28.5 ± 6.4/4.3	-14.5 ± 3.1/3.0	-18.5 ± 4.2/2.9
Gate angle variables				
Catch slip (°)	7.7 ± 3.0/1.8	9.7 ± 2.8/1.8	3.7 ± 3.2/1.2	5.6 ± 3.6/2.3
Finish slip (°)	14.1 ± 3.0/1.6	18.1 ± 3.5/2.1	8.5 ± 2.9/1.0	8.5 ± 2.0/1.5
Finish angle (°)	43.5 ± 2.3/1.4	44.2 ± 3.1/1.3	33.2 ± 1.1/1.4	32.4 ± 1.7/1.2
Arc angle (°)	105.4 ± 5.2/2.5	106.0 ± 3.2/2.2	82.0 ± 2.3/1.2	80.4 ± 3.5/2.8
Catch angle (°)	-62.0 ± 5.2/1.8	-61.8 ± 2.3/1.3	-48.8 ± 2.8/1.7	-48 ± 3.8/2.0

M1x, men’s single scull; W1x, women’s single scull; M2-, men’s coxless pairs; W2- women’s coxless pairs.

[a]Mean is the mean of the crew means, between-crew SD is the SD of the crew means, and within-crew SD is the mean of the crews' SDs across their 1-3 races (~250 to ~750 strokes).

Number of crews: 10, 8, 3 and 6 respectively.

Number of races: 17, 13, 5, 12 respectively.

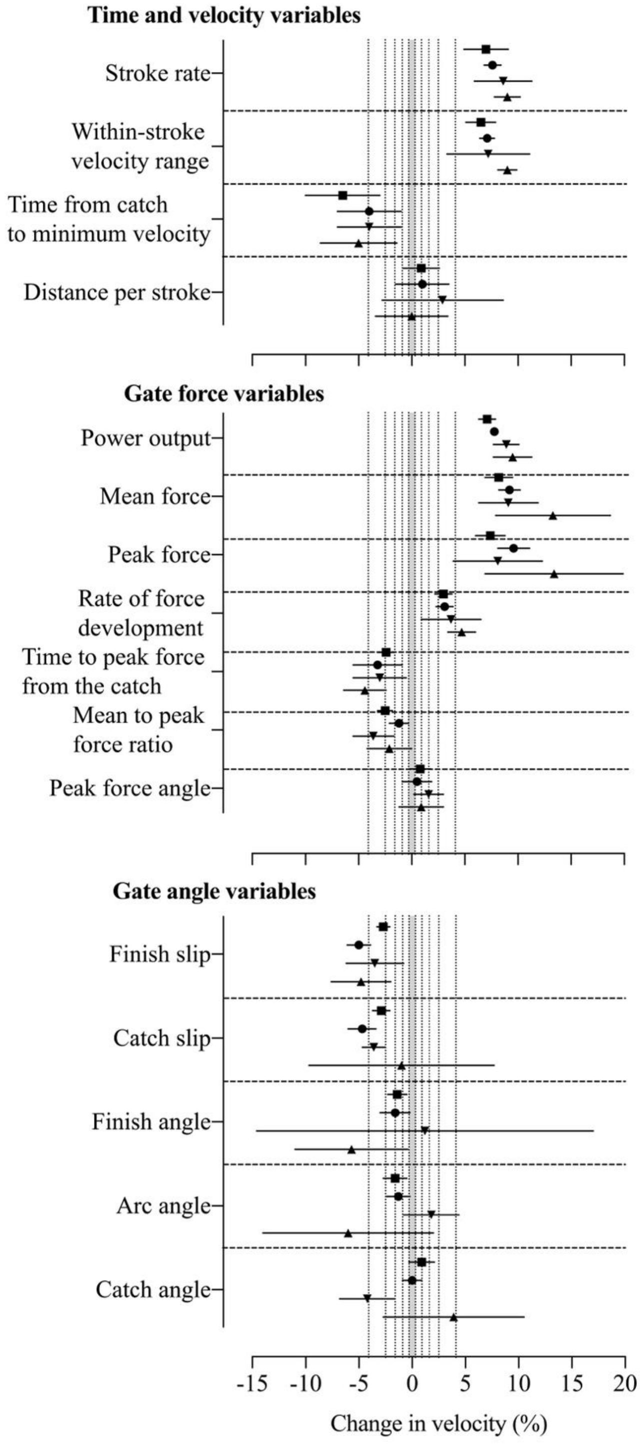

Figure 6.1 Change in boat velocity for a change in each predictor variable of two within-crew standard deviations in the four boat classes without adjustment for power output. Data are mean (%) and 90% compatibility limits. The shaded grey area covers values within the smallest important change thresholds (-0.3 to 0.3%). Vertical dotted lines delineate threshold magnitudes of small (±0.3), moderate (±0.9), large (±1.6), very large (±2.5), and extremely large (±4.1). Rejection of the non-inferiority or non-superiority hypothesis occurs when compatibility limits do not enter the grey area. Effects with compatibility limits that end within the grey area have adequate precision but are only possibly or likely substantial.

The greatest effects on velocity before adjustment were found for peak and mean force, which were extremely large, positive effects, where the non-superiority hypothesis was rejected in all boat classes ($p_{N+} \leq 0.003$). Before adjustment most effects were very large to extremely large and had sufficient precision for the true magnitudes to be very likely or most likely substantial (rejection of the non-superiority or non-inferiority hypotheses, p_{N+} or p_{N-} <0.05 or <0.005). Consistent positive effects in all boat classes were found for stroke rate, within-stroke velocity range, power output, peak and mean power, and rate of force development. Consistent negative effects in all boat classes were found for time from the catch to minimum velocity, time to peak force from the catch, and finish slip. Precision was inadequate (the non-superiority or non-inferiority hypothesis was not rejected, p_{N+} or p_{N-} >0.05) in most boat classes for distance per stroke, peak force angle, and catch angle.

After the adjustment for power, effect magnitudes were reduced (Figure 6.2 and Supplementary Table 3). Large to very large positive effects were found in most boat classes for stroke rate and distance per stroke, large to extremely large negative effects across boat classes where found for mean and peak force, and small negative effects for time to peak force from the catch were found in some boat classes where precision was sufficient for the true magnitudes of these effects to be very likely or most likely substantial (rejection of the non-substantial hypotheses, p_{N+} or p_{N-} <0.05 or <0.005). Measures that were potentially useful for practitioners, where the effects had adequate precision but were only possibly or likely substantial (one of the non-superiority or non-inferiority hypotheses was not rejected, p_{N+} or p_{N-} >0.05), include positive effects in some boat classes for within-stroke velocity range and rate of force development, and negative effects for time from the catch to minimum velocity, time to peak force from the catch, mean-to-peak force ratio, peak force angle, finish slip, arc angle, finish angle, and catch angle. Less potentially useful were observed trivial effects that had adequate precision, where the true magnitudes were possibly or likely trivial, but where only one of the superiority and inferiority hypotheses was rejected (p_{N+} or p_{N-} <0.05), found in some boat classes for rate of force development, mean-to-peak force ratio, peak force angle, catch and finish slips, arc angle, and finish angle. Only one effect was decisively trivial, where both the superiority and inferiority hypotheses were rejected (p_{N+} or p_{N-} <0.05), in women’s singles for peak force angle.

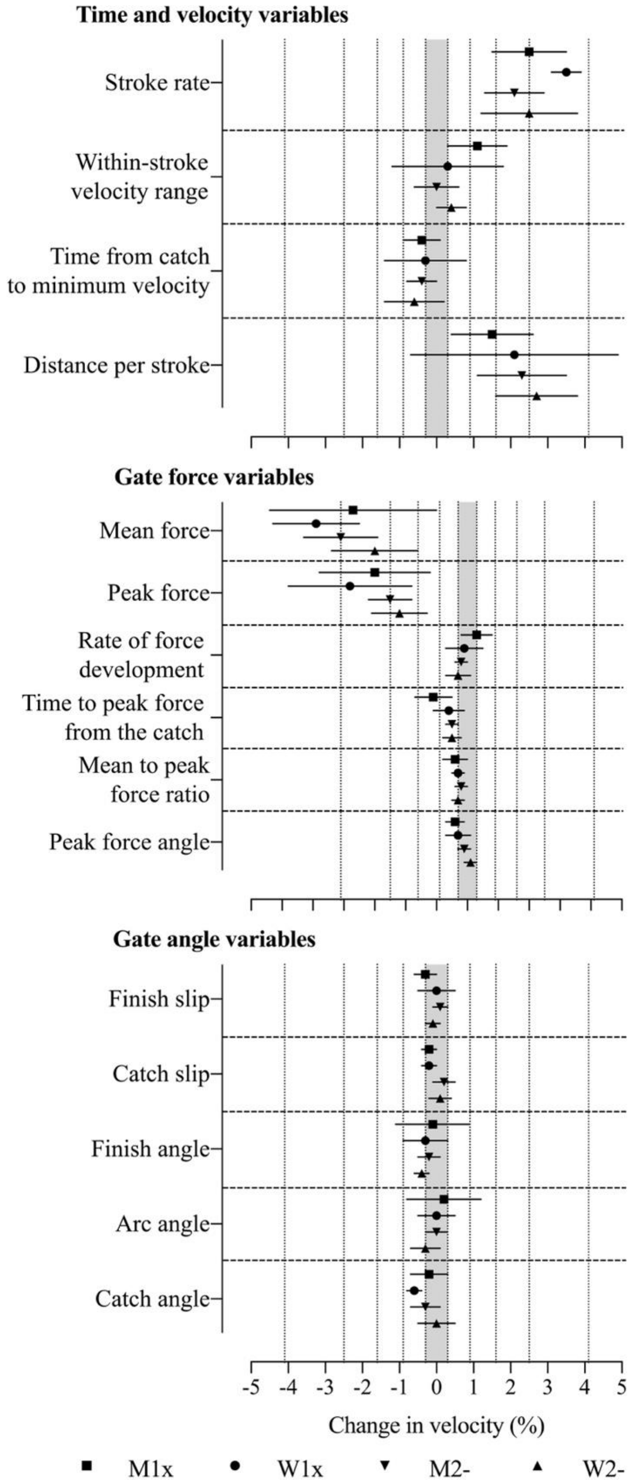

Figure 6.2 Change in boat velocity for a change in predictor variables of two within-crew standard deviations with adjustment for power output in the four boat classes. Data are mean (%) and 90% compatibility limits. The shaded grey area covers values within the smallest important change thresholds (-0.3 to 0.3%). Vertical dotted lines delineate threshold magnitudes of small (±0.3), moderate (±0.9), large (±1.6), very large (±2.5), and extremely large (±4.1). Rejection of the non-inferiority or non-superiority hypothesis occurs when compatibility limits do not enter the grey area. Effects with compatibility limits that end within the grey area have adequate precision but are only possibly or likely substantial.

The adjustment of power and stroke rate further reduced the magnitudes of most effects to the ranges of trivial to large (Figure 6.3 and Supplementary Table 4). Distance per stroke is not presented in Figure 6.3 or Supplementary Table 4, because when multiplied by stroke rate (added, after log transformation) it perfectly predicts velocity. Moderate and small positive effects were found in some boat classes for arc angle, large to very large negative effects were found across boat classes for mean and peak force, and moderate negative effects were found in some boat classes for within-stroke velocity range and catch angle where precision was sufficient for the true magnitudes of these effects to be very likely or most likely substantial (rejection of the non-substantial hypotheses, p_{N+} or p_{N-} <0.05 or <0.005). Measures that were potentially useful for practitioners, where the effects had adequate precision but were only possibly or likely substantial (one of the non-superiority or non-inferiority hypotheses was not rejected, p_{N+} or p_{N-} >0.05) after adjustment for power and stroke rate, include positive effects in some boat classes for time from the catch to minimum velocity, finish slip, finish angle, and arc angle, and negative effects for within-stroke velocity range, rate of force development, time to peak force from the catch, peak force angle, catch slip, and catch angle. Decisively trivial effects where both the superiority and inferiority hypotheses were rejected (p_{N+} or p_{N-} <0.05) were found for peak force angle and finish slip in men's singles. Trivial effects that had adequate precision, where the true magnitudes were possibly or likely trivial, but where only one of the superiority and inferiority hypotheses was rejected (p_{N+} or p_{N-} <0.05) were found in some boat classes for time to peak force from the catch, mean-to-peak force ratio, peak force angle, catch slip, and finish angle.

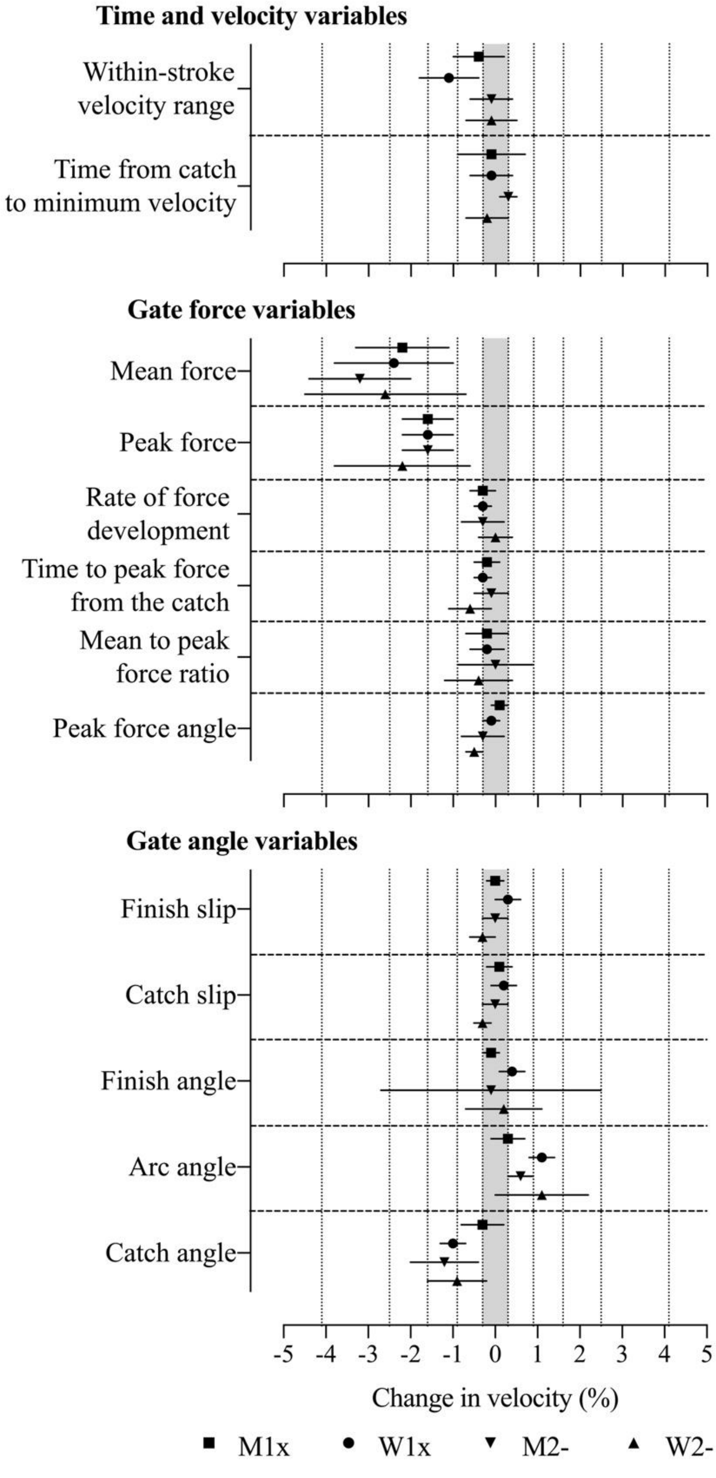

Figure 6.3 Change in boat velocity for a change in predictor variables of two within-crew standard deviations with adjustment for power output and stroke rate in the four boat classes. Data are mean (%) and 90% compatibility limits. The shaded grey area covers values within the smallest important change thresholds (-0.3 to 0.3%). Vertical dotted lines delineate threshold magnitudes of small (±0.3), moderate (±0.9), large (±1.6), very large (±2.5), and extremely large (±4.1). Rejection of the non-inferiority or non-superiority hypothesis occurs when compatibility limits do not enter the grey area. Effects with compatibility limits that end within the grey area have adequate precision but are only possibly or likely substantial.

Random error arising from the Peach or Catapult attenuates the effect of the variable on boat velocity. Random errors estimated in Chapter Three were 0.4°, 0.3° and 0.5° for Peach catch, finish, and arc angles, respectively. The attenuation, expressed as a modifying factor (Hopkins et al., 2009), was estimated using $(SD^2-e^2)/SD^2$, where SD is the within-crew standard deviation (~1.7°, ~1.3° and ~2.2°; Table 6.1) and e is the random error. The resulting factors were 0.94, 0.95 and 0.93, which are practically negligible. Random errors estimated in Chapter Four for Peach power output per stroke were -16.0 to -3.0 % (Table 4.4), representing minor smoothing of stroke-to-stroke variations in power. As such, the attenuation of relationships where power per stroke is a predictor in the current study are negligible (a modifying factor of ~0.90). The extent to which random error modifies the effects of the other predictor variables is unknown.

Differences between crews in the effect of predictor variables on velocity before adjustment are presented in Supplementary Table 5 with $p_{–}$ and p_{+} values and reference-Bayesian likelihoods of substantial and trivial effects. Between-crew differences in men's and women's singles were mostly large to extremely large and had adequate precision for the true magnitudes to be very likely or most likely substantial (rejection of the non-superiority or non-inferiority hypotheses, p_{N+} or $p_{N–}$ <0.05 or <0.005). The magnitudes of between-crew differences were similar in pairs to those in singles, but precision was inadequate (rejection of one of the non-superiority or non-inferiority hypotheses, p_{N+} or $p_{N–}$ <0.05) for some predictors in women's pairs and for most predictors in men's pairs (owing to an insufficient number of crews and races).

Between-crew differences in the effects were similar with adjustment for power and with adjustment for stroke rate and power, but sometimes a little smaller when adjusting for stroke rate and power, presented in Supplementary Table 6 (adjustment for power), and Figure 6.4 and Supplementary Table 7 (adjustment for stroke rate and power) as standard deviations. Most effects were reduced in magnitude to the range of small to large and were unclear (both substantial hypotheses were not rejected, p_{+} and $p_{–}$ >0.05). Between-crew differences were found in men's singles for most predictors, where precision was sufficient for the true magnitudes of the effect to be decisively substantial (rejection of the non-substantial hypotheses, p_{N+} or $p_{N–}$ <0.05). Between-crew differences in women's singles were decisively substantial for most oar angle variables, and some force, and time and velocity variables. Some force variables had decisively substantial between-crew differences in women's pairs. Predictors with adequate precision in some boat classes that were only possibly or likely substantial (one of the non-superiority or non-inferiority hypotheses was not rejected, p_{N+} or p_{N-} >0.05) included stroke rate, time to peak force from the catch, peak force angle, and finish angle when adjusting for power, and peak force, rate of force development, and peak force angle when adjusting for stroke rate and power.

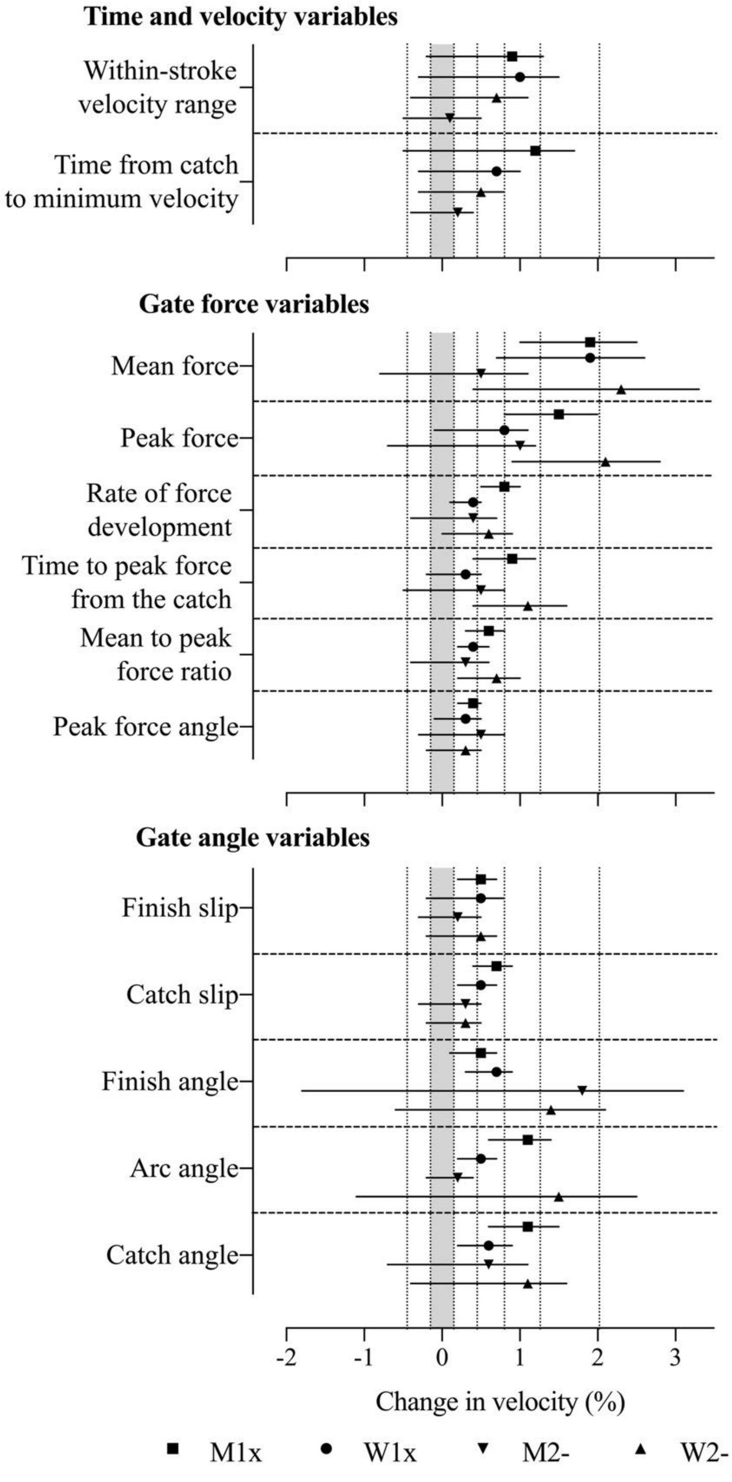

Figure 6.4 Differences between crews in the effects of the predictor variables shown in Figure 6.3 in the four boat classes with adjustment for power output and stroke rate. Data are SD (%) and 90% compatibility limits. The shaded grey area covers values within the smallest important difference thresholds (-0.15 to 0.15%). Vertical dotted lines delineate threshold magnitudes of small (±0.15), moderate (±0.45), large (±0.8), very large (±1.26), and extremely large (±2.02). Rejection of the non-inferiority or non-superiority hypothesis occurs when compatibility limits do not enter the grey area. Effects with compatibility limits that end within the grey area have adequate precision but are only possibly or likely substantial.

6.5 Discussion

Substantial stroke-to-stroke relationships between many biomechanical variables and boat velocity have been revealed in this study of National-pathway rowers performing 2000-m races in instrumented rowing boats, which can be used to guide technical analysis and feedback by practitioners. There was also evidence of substantial relationships for some variables after adjustment for power output, and power adjustment for power output and stoke rate; as such, these relationships provide potential strategies for improving boat velocity through improvement of rowing efficiency. A low risk of harm to performance (as denoted in bold in Supplementary Table 2, Supplementary Table 3, and Supplementary Table 4) was found for most effects before adjustment, and for some effects after adjustment for power and adjustment for power and stroke rate. Practitioners can take confidence in effects with a low risk of harm to performance, as they are most unlikely to have a detrimental relationship with performance. Most variables also showed evidence of substantial individual differences in their relationship with boat velocity before adjustment for power output and evidence of individual differences for some variables and in some boat classes were found after adjustment for power and adjustment for power and stroke rate.

In comparison to effects without adjustment, the adjustment for power resulted in large reductions in effect magnitudes across boat classes in most predictors, with many effects no longer having adequate precision, revealing the mediating effect of power output on many of the predictors assessed. The adjustment for power aimed to identify predictors that were associated with improved rowing efficiency, but the large to very large effects for stroke rate after adjustment for power highlighted the need for its supplementary adjustment with power. The additional adjustment for stroke rate with adjustment for power resulted in further reductions in effect magnitudes in many of the predictors assessed, albeit to a smaller extent than those observed with adjustment for power alone. However, the smaller reduction in effects after adjustment for stroke rate and power does not demonstrate that stroke rate has a smaller mediating effect than power output, as reductions in effect magnitudes similar to those with adjustment for power can be expected with adjustment for stroke rate alone given the strong relationship between stroke rate and power output (Held et al., 2020; Hofmijster et al., 2007). Extremely large positive effects were found in all boat classes for both power and stroke rate without adjustment, which agree with strong correlations with velocity for power (r = 0.44-0.67) (Coker, 2010) and stroke rate (r ≥0.66) (Kleshnev, 2001; T. P. Martin & Bernfield, 1980) reported in other studies, and promote the achievement of higher power outputs and stroke rates for performance improvement. In addition to the extremely large effects for power and stroke rate, their mediating effects on the relationships between most predictor variables with velocity highlights the importance of adjustment for both stroke rate and power output in the assessment of biomechanical variables in rowing.

Mean and peak force had the greatest modifying effects on velocity without adjustment for power, with extremely large positive effects observed in all boat classes. The effects for mean and peak force align with the moderate to large relationships (r = 0.49-0.54) between peak force and velocity observed in two elite single scullers (Coker, 2010), and likely improve velocity as a result of increased stroke power. The direction of effects for mean and peak force became negative with adjustment for power, which likely reflect faster oar angular velocities during the drive, corresponding to reduced force for a given power output per stroke as explained by the force-velocity relationship in skeletal muscle. Faster oar angular velocity may therefore benefit performance, as an optimum stroke rate for power output has not yet been identified in rowing (Held et al., 2020).

The ratio of mean-to-peak force during the drive provides a measure of force curve smoothness, with smoother force curves suggested to reduce within-stroke velocity fluctuations (R. M. Smith & Spinks, 1995), and boat drag (Greidanus et al., 2016). Smaller mean-to-peak force ratios associated with more successful rowers (R. M. Smith & Draper, 2006) agree with the very large negative effects for mean-to-peak force ratio found in some boat classes before adjustment for power. However, effects for mean-to-peak force ratio variable were mostly trivial and unclear after adjustment for power and stroke rate, whereby the relationship between force curve smoothness and rowing performance appears to be mediated by power and stroke rate. Within-stroke velocity fluctuations can also be explained by power and stroke rate, as the extremely large positive effects for within-stroke velocity range before adjustment are reduced to mostly trivial and unclear effects after adjustment for power and stroke rate. Associations between velocity fluctuations, stroke rate and power have also been established (Hofmijster et al., 2007), which relate to changes in rower centre of mass acceleration during the stroke (Hill & Fahrig, 2009).

The occurrence of peak force was investigated in the current study by assessment of the modifying effects on velocity of time from the catch to minimum velocity, rate of force development, time to peak force from the catch, and peak force angle. The location of peak force during the drive has been disputed in the literature, with initial studies promoting peak force to occur mid-drive due to the larger component of force application in the propulsive direction where the oar is perpendicular to the boat's long axis (Celentano, Cortili, Di Prampero, & Cerretelli, 1974; T. P. Martin & Bernfield, 1980). However, more recent research supports the achievement of peak force early in the drive (Coker, 2010; Hume, 2018; Kleshnev, 2006, 2007; Millward, 1987; Warmenhoven, Cobley, et al., 2017), which is suggested to increase power output through increasing area under the force-time curve, with earlier peak forces via greater rate of force development increasing the impulse achieved (Hume, 2018; Millward, 1987), resulting in a more even distribution of power through the drive and reducing within-stroke boat velocity fluctuations (Kleshnev, 2006). More pronounced front-peaked force-angle curves have also been associated with rowing success in experienced female scullers, relating to increased rate of force development and the earlier location of peak force (Warmenhoven, Cobley, et al., 2017). The decisively substantial negative effects for time from the catch to minimum velocity and time to peak force from the catch, and the decisively substantial positive effects for rate of force development before adjustment indicate a performance benefit for earlier peak forces. However, the reduction of effect magnitudes and loss of adequate precision in most boat classes after adjustment for power for time from the catch to minimum velocity, time to peak force from the catch, and rate of force development suggest earlier peak forces improve velocity through increasing power output.

The increased precision in positive effects for distance per stroke with adjustment for power, in comparison to without adjustment, can be expected to reflect displacement in the calculation of velocity, whereby an increase in the distance travelled for a given power output will result in a higher velocity. Research investigating distance per stroke and stroke rate in elite rowers during 2000-m racing found an emphasis on distance per stroke more so than stroke rate in singles, whereas pairs appeared to achieve higher stroke rates at the cost of distance per stroke (Kleshnev, 2001), although the results of the current study were not consistent with these findings.

Inconsistencies in the precision of effects between boat classes before adjustment for power and stroke rate make interpretation of the importance of catch and finish angles difficult. Larger negative catch and positive finish angles are understood to be advantageous, given propulsive work is greater for a given applied force where arc angle increases (Warmenhoven et al., 2018). However, consistent modifying effects with adequate precision across boat classes were not established before adjustment for power and stroke rate, aligning with research that has also failed to establish consistent relationships between oar angle measures and boat velocity (Coker, 2010). Nevertheless, the decisively substantial effects in some boat classes for catch angle and arc angle, and the likely or possibly substantial effects in the remaining boat classes for these variables after adjustment for power and stroke rate, indicate larger catch angles to be advantageous to performance. The negative effects for catch angle likely illustrate lift forces acting on the blade at the catch, where the blade acts as a hydrofoil, increasing forward propulsion of the boat through improved mechanical efficiency (Coker, 2010; Pulman, 2005; Robert et al., 2019; Warmenhoven et al., 2018).

Catch and finish slips are a measure of the angle rowed through at either end of the stroke that does not contribute to forward propulsion of the boat. The measurement of catch and finish slips by the use of predetermined force thresholds, as those used in the current study, have been criticised for lack of individualisation of the force threshold corresponding to forward boat propulsion, and for measurement inaccuracies resulting from resistive forces at the blade erroneously reducing slip values (Macrossan & Macrossan, 2006). However, the extremely large negative effects observed in most boat classes without adjustment for power supports the use of catch and finish slip assessment with predetermined force thresholds. Further, the reduction of effect magnitudes across boat classes for catch and finish slips after adjustment for power, indicate their effect on velocity corresponds to increased power, likely via increasing the area under the force-angle curve, and therefore propulsive work.

The between-crew differences for catch angle in men’s singles after adjustment for power and stroke rate, and for most predictors in some boat classes before adjustment for power (Figure 6.4 and Supplementary Table 6 respectively), demonstrate the crew-specific nature of relationships between some measures of rowing technique and boat velocity. Where a predictor has a substantial mean effect and substantial between-crew differences, both with adequate precision, we can expect a change in the predictor to be associated a change in performance in the same direction in most rowers. However, the predictor would be best investigated on an individual basis to determine whether it is an avenue for substantial performance enhancement in each crew. The random effect solutions for crew identity presents individual differences from the mean modifying effect for each crew, allowing identification of crews with greater or smaller effects for each variable. An individual approach to technical analysis using methods such as these is recommended for predictors where between-crew differences were evident, enabling individualised coaching feedback.

6.5.1 Limitations

Given the assessment of predictors separately, some effects will represent underlying relationships between the predictors, whereby, a change in one predictor likely contributes to changes in others. Therefore, the effects presented cannot be expected to have an additive enhancement on performance (other than those in Figure 6.2 with power output, and those in Figure 6.3 with power output and stroke rate). Rather, the results present the extent to which predictors are associated with a change in velocity, informing the assessment of these variables by practitioners, with the adjustment for power and stroke identifying predictors mediated by these variables. Additionally, non-final races were included in the analyses where crews may have implemented sub-maximal pacing strategies. However, as the current study assessed stroke-to-stroke changes in predictors, variations in predictors due to changes in pacing strategy further explain relationships between predictors and boat velocity.

6.5.2 Practical Applications

- Higher stroke rates should be targeted in racing to improve rowing performance.
- Rower force development should be prioritised as a key component of power output and boat velocity.
- The achievement of greater catch angles should be targeted in rowers, and likely improve velocity via the improved mechanical efficiency associated with lift forces at the catch.

- Relationships between some measures of rowing technique and performance are variable between rowers and are best assessed on an individual basis to determine areas of coaching focus.
- Stroke rate and power output have mediating effects on many biomechanical rowing variables, and their adjustment should be considered for future analyses of relationships between the variables presented and velocity.

6.6 Conclusion

The results presented suggest key areas for rowing performance improvement are force development, the achievement of higher stroke rates, reduction of catch and finish slips, and the achievement of greater catch angles. An individual approach to technical analysis and feedback is recommended, given the potentially wide between-crew differences in the effect of technique on performance without adjustment for power. The adjustment of power output and stroke rate is recommended for future research investigating relationships between biomechanical variables and velocity in rowing, due to the mediating effects of power and stroke rate observed in this study.

Chapter Seven: Relationships between measures of boat acceleration and performance in rowing, with and without controlling for stroke rate and power output

7.1 Abstract

Purpose: Boat acceleration profiles provide a valuable feedback tool by reflecting both rower technique and force application. Relationships between measures of boat acceleration and velocity to inform interpretation of boat acceleration profiles in rowing were investigated here. **Methods:** Thirteen male singles, nine female singles, eight male pairs, and seven female pairs participated (national and international level, age 18-27 y). Data from each stroke for 74 2000-m races were collected using Peach PowerLine and OptimEye S5 GNSS units. General linear mixed modelling established modifying effects on velocity of two within-crew SD of boat acceleration variables for each boat class, without and with adjustment for stroke rate and power, to identify potential performance-enhancement strategies for a given stroke rate and power. Measures of acceleration at six peaks or dips, and six measures of the rate of change (jerk) between these peaks and dips were analysed. Results were interpreted using rejection of non-substantial and substantial hypotheses with a smallest substantial change in velocity of 0.3%. **Results:** Several boat acceleration measures had decisively substantial effects (-2.4-2.5 %) before adjustment for stroke rate and power. Most effect magnitudes reduced after adjustment for stroke rate and power, although maximum negative drive acceleration, peak drive acceleration, jerk during the mid-drive phase, and jerk in the late recovery remained decisively substantial (-1.8-1.9 %) in some boat classes. **Conclusion:** Greater absolute values of maximum negative drive acceleration and jerk in the late recovery are related to improved performance, likely reflecting delayed rower centre-of-mass negative acceleration in preparation for the catch. Greater absolute values of peak drive acceleration, first peak acceleration, and jerk in the early and mid-drive are also associated with improved performance, likely reflecting propulsive force during the drive. These proposed mechanisms provide potential strategies for performance enhancement additional to increases in stroke rate and power output.

7.2 Introduction

Boat acceleration profiles provide insight into rower force application and centre-of-mass (COM) movement and are frequently used by coaches and sport scientists to provide feedback on rowing technique. Rower COM acceleration occurs in the direction of boat travel during the drive (propulsive) phase and is reversed during the recovery (non-propulsive) phase, contributing to fluctuations in boat acceleration throughout the stroke (Kleshnev, 2010a). Discontinuous force application throughout the stroke, and the timing of force application with rower COM acceleration further contributes to boat acceleration fluctuations (Kleshnev, 2010a; Soper & Hume, 2004a), with the acceleration profile closely reflecting force curve shape during the drive (Draper & Smith, 2006). Boat acceleration profiles have been used for several years by coaches and sport scientists as a method of biomechanical and technical analysis. However, current interpretation of acceleration profiles is often informed by the comparison of profiles to those produced by successful rowers, given few studies have investigated relationships between the acceleration profile and rowing performance (Kleshnev, 2002, 2010a; R. M. Smith & Draper, 2006).

Research investigating relationships between boat acceleration and rowing performance is mostly limited to the assessment of men's pairs, often with small sample sizes, and involves the comparison of crews with varying success levels (Kleshnev, 1998, 2002, 2010a; R. M. Smith & Draper, 2006), adding to the difficulty faced by coaches and sport scientists in identifying favourable measures of boat acceleration. Conflicting positive (R. M. Smith & Draper, 2006) and negative (Kleshnev, 2002, 2010a) relationships with rowing success level have been observed for the magnitude of maximum negative acceleration occurring early in the drive (marker 1 in Figure 7.1) in elite men's pairs. Greater magnitudes of maximum negative drive acceleration occur in sweep (one oar per rower) compared to sculling (two oars per rower), and male compared to female boat classes (Kleshnev, 1998). Jerk, the rate of acceleration change (Eager, Pendrill, & Reistad, 2016) is greater following maximum negative drive acceleration (markers 1 to 2 in Figure 7.1) in more successful crews, as is an earlier occurrence of positive boat acceleration (Kleshnev, 2002, 2010a). Acceleration at the first positive peak of acceleration occurring during the drive (marker 2 in Figure 7.1) is positively associated with rowing success level (Kleshnev, 2010a), with larger magnitudes in sweep compared to sculling boat classes (Kleshnev, 1998). The subsequent dip in acceleration following the first peak (marker 3 in Figure 7.1) also has a positive association with crew success level (Kleshnev, 2010a). Negative associations exist between peak drive acceleration (marker 4 in Figure 7.1) and crew success (Kleshnev, 2002). Nevertheless, the small sample sizes and somewhat conflicting results of these studies make inferences regarding favourable acceleration profiles difficult. Furthermore, only a small section of the acceleration profile (up to marker 4 in Figure 7.1) has been examined, whereby the association between boat acceleration in the recovery phase and rowing performance is not known.

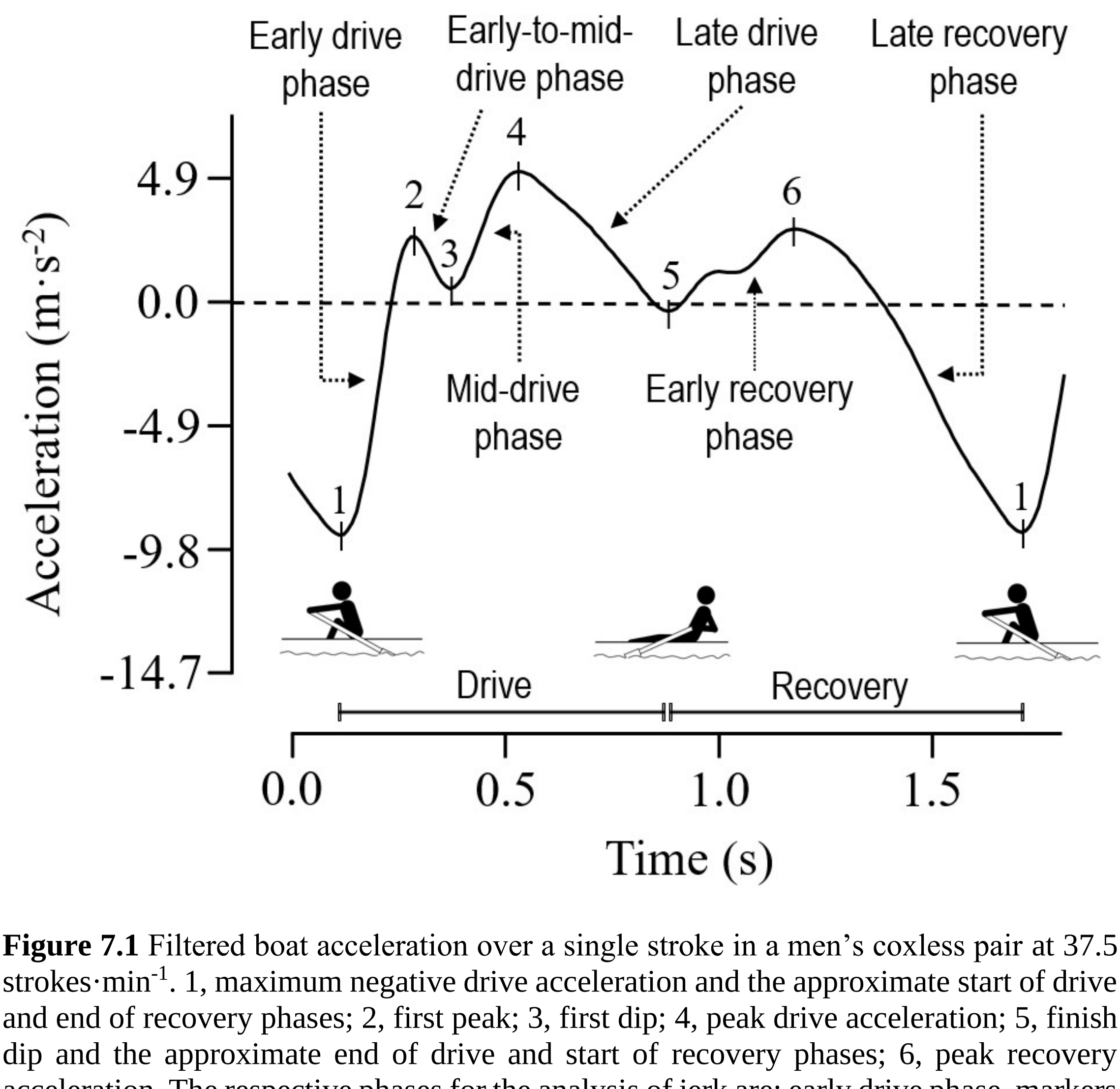

Figure 7.1 Filtered boat acceleration over a single stroke in a men's coxless pair at 37.5 strokes·min^{-1}. 1, maximum negative drive acceleration and the approximate start of drive and end of recovery phases; 2, first peak; 3, first dip; 4, peak drive acceleration; 5, finish dip and the approximate end of drive and start of recovery phases; 6, peak recovery acceleration. The respective phases for the analysis of jerk are: early drive phase, markers 1 to 2; early-to-mid drive phase, markers 2 to 3; mid-drive phase, markers 3 to 4; late drive phase, markers 4 to 5; early recovery phase, markers 5 to 6; late recovery phase, marker 6 to 1 of the next stroke. Rower position corresponding to the acceleration profile is shown above.

Further research investigating the boat acceleration profile across the whole stroke in detail, and its relationship with rowing performance, would better inform how rower COM movement and force application impact rowing performance, and therefore better inform the interpretation of boat acceleration profiles in rowing. Given the magnitudes of acceleration at the first positive peak and the maximum negative drive acceleration are related to stroke rate (Kleshnev, 2010a), research investigating the boat acceleration profile when adjusting for stroke rate would ensure any relationships between boat acceleration and performance are not simply a product of higher stroke rates, and inform potential strategies for enhancing performance in addition to increases in stroke rate. Similarly, adjusting for power output when assessing the relationship between boat acceleration and performance would reveal performance effects that are related to improved rowing efficiency rather than the power applied. Therefore, this study aims to inform the interpretation of the boat acceleration profile in rowing by investigating the effect of the boat acceleration profile on boat velocity in men's and women's singles and coxless pair boats during 2000-m racing without and with adjustment for stroke rate and power. The outcomes of this investigation will inform which aspects of the boat acceleration profile correspond with the greatest improvements in rowing performance, and how these relationships are mediated by stroke rate and power output, advising areas where additional performance improvements can be achieved.

7.3 Methods

7.3.1 Participants

Twenty-one female (age 20.6 ± 2.2 y; height 176.6 ± 6.2 cm; body mass 72.5 ± 7.9 kg) and 23 male (age 21.0 ± 2.5 y; height 189.5 ± 8.0 cm; body mass 85.8 ± 9.7 kg) national and international-level rowers who performed regular training volumes of approximately 17-22 $h \cdot wk^{-1}$ volunteered for this study. Participants provided informed consent prior to commencement of the study. The study was approved by the University Human Research Ethics Committee and written consent was obtained from participants.

7.3.2 Study design

The study was conducted during three national regattas held at the Sydney International Regatta Centre, Australia. A total of 74 2000-m races were recorded from 14 male single crews (25 races), nine female single crews (18 races), nine male coxless pair crews (18 races), and seven female coxless pair crews (13 races). Of the men's singles crews, six competed in lightweight events (10 races), as did one of the female single crews (two races). Crew age categories were <19 y (one crew), <21 y (seven crews), <23 y (24 crews), and Senior (no age restriction; seven crews). Races recorded were heats (32 races), repêcharges (four races), semi-finals (eight races) and finals (30 races). The number of races analysed ranged from one to five for any given crew; these repeated measurements were accounted for in the mixed model, as described in the statistical analyses section. One participant in the men's single and one in the women's single also competed in the coxless pair, and three male and one female participant competed in two coxless pair crews (i.e., with a different pair partner, assessed as separate crews). Crews were given no instructions from the researchers regarding race strategy or stroke rate. Power output was collected per stroke from races using Peach PowerLine instrumentation systems (Peach Innovations, UK), calibration of force and gate angle was performed immediately prior to each race. Boat velocity and acceleration was collected at a sample rate of 10 Hz and 100 Hz respectively, using OptimEye S5 GNSS units (Catapult, Australia) attached to the stern canvas of participant boats. Both Peach PowerLine instrumentation and Catapult GNSS systems are used frequently within elite rowing programs. Acceptable levels of validity have been established for measures of rowing velocity from Catapult GNSS units (0.2 % standard error of the estimate) (T. B. Smith & Hopkins, 2012) and for force and oar angle (<8.9 N and <0.9 ° standard error of the estimate, respectively) by Peach instrumentation systems (Coker et al., 2009). The Peach system calculates power from measures of gate angular velocity, gate force in the direction of the boat's long axis, and the ratio of the oar outboard (distance from the collar to blade tip) to total length. Power from the Peach system represents a proxy measure of the true mechanical power output (Hofmijster et al., 2018). Venue environmental conditions (collected at 1-min intervals from six weather stations positioned at water level along the 2000 m course) were: 21.9 ± 2.4 °C air temperature (mean ± SD); 26.0 ± 1.2 °C water temperature; 70.5 ± 20.4 % relative humidity; and 1.3 ± 0.5 $m \cdot s^{-1}$ wind speed, in a predominantly cross direction on stroke side (port).

7.3.3 Data processing

Acceleration and velocity data was exported from the software Logan (version 48.41, Australian Institute of Sport, Australia) and processed in the desktop version of R Studio (version 1.2.5, R Foundation, Austria). A low-pass 4th order Butterworth filter with 6 Hz cut-off frequency was applied to acceleration data (the choice of cut-off frequency was based on residual analysis and visual inspection of raw and smoothed curves).

Three peaks and three dips in acceleration were identified in each stroke, as shown in the acceleration profile of a single stroke in a men's coxless pair crew in Figure 7.1, and from a crew in each of the four boat classes in Figure 7.2. The variable maximum negative drive acceleration was the largest negative acceleration and was used to define the start and end of each stroke (marker 1 in Figure 7.1). The variable peak drive acceleration was the largest positive acceleration occurring between 25 to 66 % of total stroke duration (marker 4 in Figure 7.1; this range ensured the first peak and finish peak were not identified as this variable; as such, if the absolute maximal peak acceleration during the drive phase occurred at the first peak it was not marked as the peak drive acceleration variable, and the peak drive acceleration variable was therefore not the true maximum in acceleration during the drive phase). The variable peak recovery acceleration was the largest positive acceleration occurring later than 0.3 s after the peak drive acceleration variable (marker 6 in Figure 7.1; the 0.3 s delay ensured the point identified occurred in the recovery phase and was not a subsequent acceleration peak occurring in the drive phase). The finish dip variable was marked as the first occurrence after the location of the peak drive acceleration variable where acceleration increased and was less than 2.45 $m \cdot s^{-2}$ (marker 5 in Figure 7.1; the 2.45 $m \cdot s^{-2}$ threshold ensured any acceleration dips occurring during the drive phase after the peak drive acceleration variable were not marked as the finish dip variable). The first acceleration peak variable was the first occurrence after the maximum negative drive acceleration of a jerk of less than 0.20 $m \cdot s^{-3}$, where acceleration was greater than -0.98 $m \cdot s^{-2}$ (marker 2 in Figure 7.1; these thresholds allowed identification of a plateau in acceleration, or a reduction in jerk that occurred early in the drive when no peak occurred, such as that at marker 2 in Figure 7.2 for the Women's single). A reduction in jerk was identified in the absence of a peak for the first acceleration peak variable, as shown at marker 2 in Figure 7.2 for the Women's single, in approximately 7 % of the strokes analysed. The first acceleration dip variable was the first increase in acceleration that occurred following the first peak variable (marker 3 in Figure 7.1). For strokes where a reduction in jerk or plateau in acceleration were identified in the absence of a peak for the first peak variable, the first dip variable was excluded from analyses as it did not occur either (marker 2 in Figure 7.2 for the Women's single).

For the purposes of describing the stroke in this study, the drive phase was defined as between maximum negative drive acceleration and the finish dip, and the recovery phase was defined as between the finish dip and maximum negative drive acceleration of the following stroke (Figure 7.1).

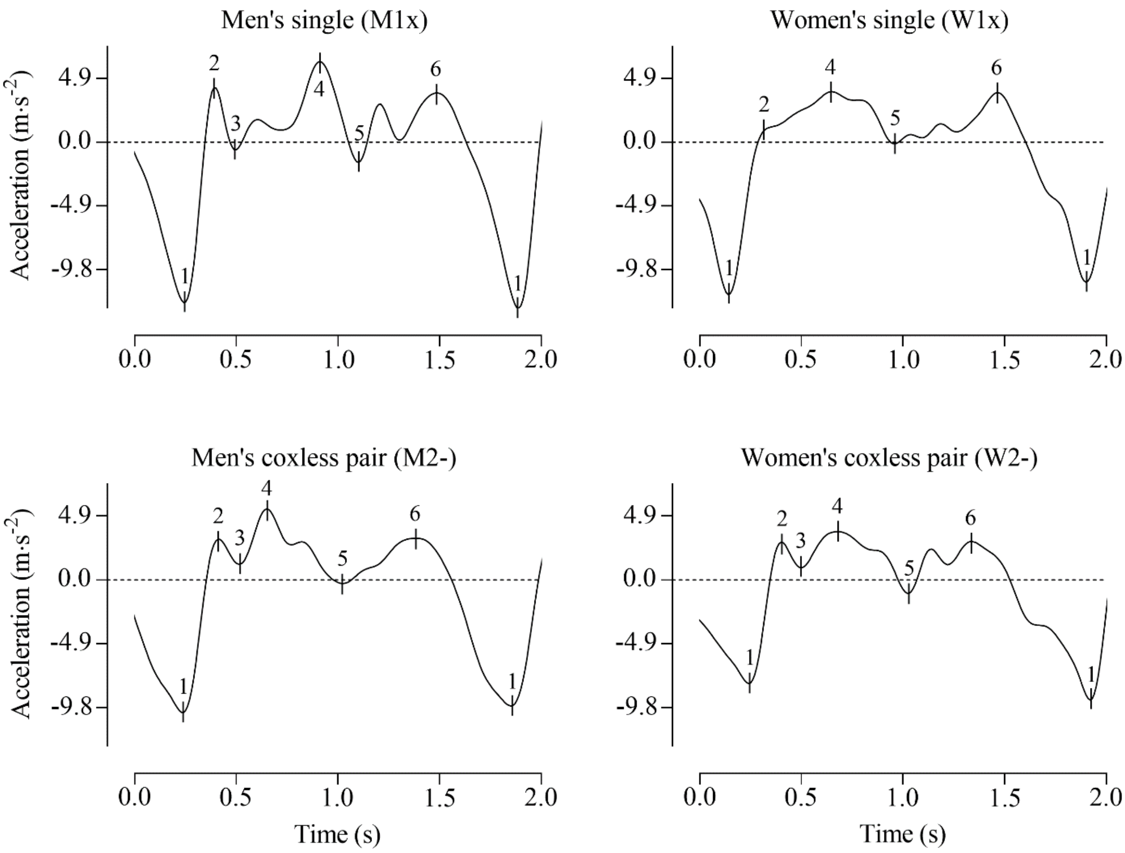

Figure 7.2 Filtered boat acceleration over a single stroke from a crew in each of the four boat classes. 1, maximum negative drive acceleration; 2, first peak; 3, first dip; 4, peak drive acceleration; 5, finish dip; 6, peak recovery acceleration. Strokes rates for the four profiles are: 36.6 strokes·min^{-1}, men's singles; 33.9 strokes·min^{-1}, women's singles; 37.5 strokes·min^{-1}, men's coxless pairs; 35.9 strokes·min^{-1}, women's coxless pairs.

Jerk, the rate of acceleration change (m·s^{-3}), was calculated from the absolute change in acceleration over the phase duration, for six phases per stroke using the three peak and dips in acceleration defined above (Figure 7.1). The six phases were: early drive (between maximum negative drive acceleration and the first peak in the early drive); early-to-mid-drive (between the first peak and the first dip); mid-drive (between the first dip and peak drive acceleration); late drive (between peak drive acceleration and finish dip); early recovery (between finish dip and peak recovery acceleration); and late recovery (between peak recovery acceleration and maximum negative drive acceleration of the next stroke).

Where the first dip did not occur (i.e., acceleration did not decrease or plateau following the first peak) jerk in the mid-drive was calculated between the first peak and peak drive acceleration.

Stroke rate (strokes·min^{-1}) was calculated from the duration between the start and end of each stroke. Velocity per stroke (m·s^{-1}) was the mean velocity between the start and end of each stroke. Power (W) per stroke was exported from Peach units and aligned from the first stroke of the race with acceleration outputs per stroke in R studio. Peach units use gate angle velocity, gate force in the direction of the boat's long axis, and the oar outboard (distance from the collar to blade tip)-to-total length ratio to calculate power.

The first ten strokes of each race were excluded from analyses in order to assess strokes where boat velocity was reasonably consistent, given these strokes encompass an initial acceleration phase of the boat from a stationary starting position and include partial strokes that are not representative of a typical rowing stroke. The last ten strokes were excluded from analyses, given that large changes in velocity can occur at the end of the race, such as a sprint to the line involving partial strokes to gain a desired a finishing position, or a substantial decrease in velocity and stroke rate where the race outcome is already secured. Outlier stroke values for each predictor variable were identified as those with a standardised difference from the mean greater than 4.5 (Hopkins et al., 2009), where the mean and the standardising SD were the running mean and running standard deviation for up to 30 strokes preceding and up to 30 strokes following the given stroke (depending on the location of the stroke in the race). A second pass of the running mean and running standard deviation was used to eliminate visually obvious outliers that were missed in the first pass. Additional outliers were identified as strokes with a standardised residual greater than 4.5 after running the statistical analyses (Hopkins et al., 2009). All outliers identified were excluded from analysis and ranged from 0.4% to 0.9% of the total strokes recorded per boat class.

7.3.4 Statistical analysis

Each gender and boat class were analysed separately with the general linear mixed-model procedure (Proc Mixed) in the Studio University edition of the Statistical Analysis System (version 9.4, SAS Institute, Cary NC). The modelling was similar to that in Chapter Six, where a stroke-to-stroke analysis of the effect of biomechanical measures of rowing technique on boat velocity was performed. The mean modifying effect on velocity of a two standard deviation (SD) within-crew change of each predictor (described above and presented in Table 7.1) was estimated from the values for each predictor per stroke and the corresponding mean boat velocity per stroke. Mean boat velocity was taken from the next stroke for the analysis of jerk in the late recovery, as this variable occurred late in the stroke and is expected to affect the velocity of the following stroke. The fixed effects in the model, predicting the logarithm of boat velocity (V), were each predictor variable analysed separately as linear predictors. Separate analyses were conducted to adjust for stroke rate, and to adjust for power output (P, the sum of both oars) and stroke rate. Fixed effects in these models were log(stroke rate) (adjusting log(V) for stroke rate), and log(P) and log(stroke rate) (adjusting log(V) for power output and stroke rate), and each predictor separately as linear predictors. In these analyses log(V) predicted by log(P) allows estimation of k and x in the kinetic equation $V = k \cdot P^x$. Random effects in the model were: crew identity (to adjust for consistently better or worse velocity of each crew across all races); crew identity interacted with log(P) (representing individual differences in the exponent x, and allowing for this term and crew identity to be correlated via an unstructured covariance matrix); the given predictor interacted with crew identity (to estimate individual differences between crews in the effect of the variable, and to account for differences in the number of repeated measurements [i.e., races analysed] between crews); race identity (to adjust for between-race changes in mean velocity due to changes in environmental conditions [such as wind and temperature] and the efficiency of the crew); and a different residual error for each crew (representing stroke-to-stroke variability in velocity [e.g., due to wind gusts or the blade catching water on the recovery] not accounted for by the other effects). The random effects for race identity and the different residuals for crews account for environmental effects, which therefore do not contribute directly to the effects of acceleration variables on boat velocity.

A smallest substantial change in velocity of 0.3% was assumed, given the 1.0% race-to-race variation in 2000-m race times of elite rowers (T. B. Smith & Hopkins, 2011). Corresponding magnitude thresholds for changes in velocity were: <0.3% trivial, ≥0.3% small, ≥0.9% moderate, ≥1.6% large, ≥2.5% very large, and ≥4.1% (≤-3.9% for negative effects) extremely large (Hopkins et al., 2009). To evaluate magnitudes of SDs representing between-crew differences the magnitude thresholds are one-half of those in the above scales: <0.15% trivial, ≥0.15% small, ≥0.45% moderate, ≥0.8% large, ≥1.3% very large, and ≥2.0% extremely large (T. B. Smith & Hopkins, 2011).

Sampling uncertainty in the estimates of effects is presented as 90% compatibility limits. Decisions about magnitudes accounting for the uncertainty were based on one-sided interval hypothesis tests, where an hypothesis of a given magnitude (substantial, non-substantial) was rejected if the 90% compatibility interval fell outside that magnitude (Hopkins, 2020). P-values for the tests were the areas of the sampling distribution of the effect (t for means, z for variances) falling in the hypothesized magnitude, with the distribution centred on the observed effect. Hypotheses of inferiority (substantial negative) and superiority (substantial positive) were rejected if their respective p-values (p_{-} and p_{+}) were <0.05; rejection of both hypotheses represents a decisively trivial effect in equivalence testing. When only one hypothesis was rejected, the p-value for the other hypothesis, when >0.25, was interpreted as the posterior probability of a substantial true magnitude of the effect in a reference-Bayesian analysis with a minimally informative prior (Hopkins, 2019) using the following scale: >0.25, possibly; >0.75, likely; >0.95, very likely; >0.995, most likely (Hopkins et al., 2009); the probability of a trivial true magnitude ($1 - p_{-} - p_{+}$) was also interpreted, when >0.25, with the same scale. Probabilities were not interpreted for effects that were unclear (had inadequate precision at the 90% level, defined by failure to reject both hypotheses, p_{-}>0.05 and p_{+}>0.05). Effects with adequate precision at the 99% level (p_{-}<0.005 or p_{+}<0.005) are shown in bold in supplementary tables and represent effects that have a conservative low risk of harm (association with reduced velocities). The hypothesis of non-inferiority (non-substantial-negative) or non-superiority (non-substantial-positive) was rejected if its p value ($p_{N-} = 1 - p_{-}$ or $p_{N+} = 1 - p_{+}$) was <0.05, representing a decisively substantial effect in minimal-effects testing: very likely or most likely substantial.

7.4 Results

Mean values for predictor variables with between-crew and within-crew SD are presented in Table 7.1. Within-crew SD indicate half of the range that effects for predictors were assessed over.

Table 7.1 Characteristics of boat velocity, stroke rate, and power, and the predictor variables in the four boat classes. Data are mean ± between-crew SD/within-crew SD[a].

	Singles		Coxless pairs	
	Men (M1x)	Women (W1x)	Men (M2-)	Women (W2-)
Boat velocity ($m{\cdot}s^{-1}$)	4.60 ± 0.10/0.19	4.13 ± 0.09/0.25	4.88 ± 0.10/0.25	4.34 ± 0.13/0.21
Stroke rate ($strokes{\cdot}min^{-1}$)	35.1 ± 1.8/1.9	32.5 ± 1.1/1.7	37.2 ± 1.2/1.9	35.5 ± 1.8/1.9
Boat power (W)[b]	337 ± 38/34	221 ± 21/24	704 ± 60/88	481 ± 40/59
Acceleration				
Max negative drive ($m{\cdot}s^{-2}$)	-11.8 ± 1.4/1.2	-10.3 ± 1.6/0.9	-11.1 ± 1.0/1.3	-9.02 ± 1.4/1.1
First peak ($m{\cdot}s^{-2}$)	2.35 ± 0.98/0.59	2.55 ± 0.98/0.49	2.84 ± 0.69/0.69	2.26 ± 0.78/0.69
First dip ($m{\cdot}s^{-2}$)	0.20 ± 0.98/0.39	0.69 ± 0.69/0.29	1.18 ± 0.78/0.39	0.69 ± 0.49/0.39
Peak drive ($m{\cdot}s^{-2}$)	5.20 ± 0.78/0.39	3.82 ± 0.39/0.29	5.39 ± 0.29/0.49	3.92 ± 0.39/0.39
Finish dip ($m{\cdot}s^{-2}$)	-0.59 ± 0.39/0.29	-0.59 ± 0.29/0.20	-0.29 ± 0.39/0.29	-0.59 ± 0.29/0.20
Peak recovery ($m{\cdot}s^{-2}$)	3.04 ± 0.78/0.39	2.75 ± 0.69/0.29	3.24 ± 0.49/0.39	2.94 ± 0.39/0.39
Jerk				
Early drive ($m{\cdot}s^{-3}$)	83 ± 15/13	72 ± 1 8/8.8	76 ± 10/14	62 ± 8.8/13
Early-to-mid-drive ($m{\cdot}s^{-3}$)	-15 ± 12/7.8	-22 ± 11/4.9	-19.6 ± 7.8/7.8	-18.6 ± 4.9/6.9
Mid-drive ($m{\cdot}s^{-3}$)	15.7 ± 7.8/2.9	8.8 ± 3.9/2.0	26.5 ± 3.9/6.9	15.7 ± 3.9/6.9
Late drive ($m{\cdot}s^{-3}$)	-29.4 ± 1.2/3.9	-18.6 ± 8.8/2.9	-17.7 ± 2.9/2.0	-15.7 ± 6.9/2.0
Early recovery ($m{\cdot}s^{-3}$)	7.8 ± 2.9/2.0	7.8 ± 2.0/2.0	10.8 ± 2.0/2.0	9.8 ± 2.9/2.0
Late recovery ($m{\cdot}s^{-3}$)	-35.3 ± 6.9/5.9	-27.5 ± 5.9/3.9	-29.4 ± 3.9/4.9	-23.5 ± 4.9/3.9

M1x, men's singles; W1x, women's singles; M2-, men's coxless pairs; W2- women's coxless pairs; Max, maximum.

[a]Mean is the mean of the crew means, between-crew SD is the SD of the crew means, and within-crew SD is the mean of the crews' SDs across their 1-3 races (~250 to ~750 strokes).
[b]Boat power is the sum of power from both oars.
Number of crews: 14, 9, 9 and 7 respectively.
Number of races: 25, 18, 18, 13 respectively.

Before adjustment, consistent positive effects for jerk in the early drive, consistent negative effects for jerk in the late recovery and maximum negative drive acceleration were found in all boat classes, which were decisively substantial (Figure 7.3 and Supplementary Table 8 with p_{-} and p_{+} values and reference-Bayesian likelihoods of substantial and trivial effects). Positive effects for jerk in the mid-drive and early recovery, first dip, peak drive, and peak recovery acceleration, and negative effects for jerk in the early drive and late drive were found in some boat classes (those with 90% compatibility intervals entirely in substantial values in Figure 7.3), which were decisively substantial. Measures that had adequate precision and observed substantial effects that were only possibly or likely substantial (only one of the superiority and inferiority hypotheses was rejected, p_{+} or p_{-} >0.05), include positive effects in some boat classes for jerk in the early recovery, first peak, peak drive, and peak recovery acceleration, and negative effects in some boat classes for jerk in the early-to-mid-drive and the late drive, first dip and finish dip acceleration (those with more than half of the 90% compatibility intervals overlapping substantial values in Figure 7.3). Only one effect was decisively trivial, where both the superiority and inferiority hypotheses were rejected (p_{+} and p_{-} <0.05), in men’s pairs for first dip acceleration. Trivial observed effects that had adequate precision but were only possibly or likely trivial were found in some boat classes for jerk in the late drive, first dip and finish dip acceleration (those with less than half of the 90% compatibility intervals overlapping substantial values in Figure 7.3).

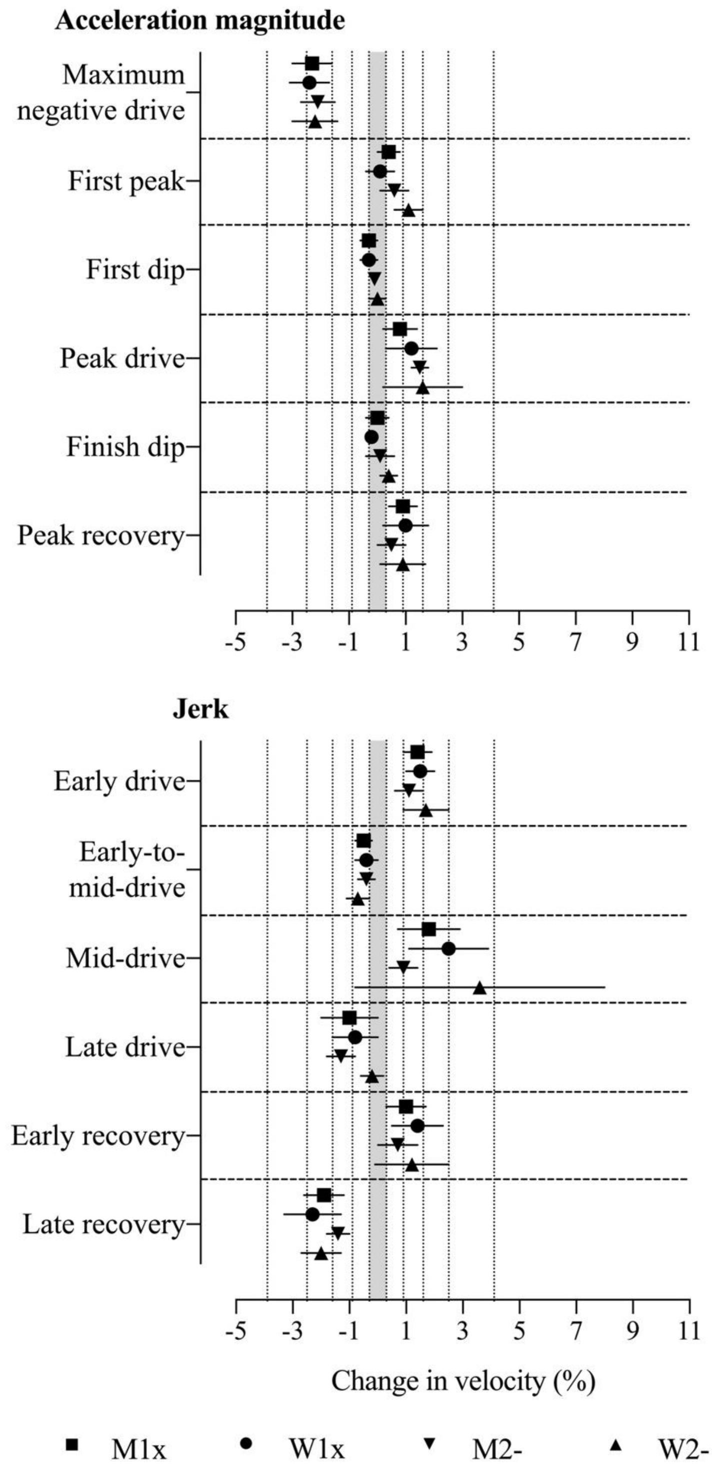

Figure 7.3 Change in boat velocity for a change in each predictor variable of two within-crew standard deviations without adjustment for stroke rate or power output. Data are mean (%) and 90% compatibility intervals. The shaded grey area covers trivial values (values within the smallest substantial change thresholds, -0.3 to 0.3%). Vertical dotted lines delineate threshold magnitudes of small (±0.3), moderate (±0.9), large (±1.6), very large (±2.5), and extremely large (4.1, -3.9%). Effects with compatibility intervals that do not enter the grey area are decisively (very likely or most likely) substantial. Effects with compatibility intervals that end within the grey area have adequate precision (possibly or likely substantial or trivial).

After the adjustment for stroke rate, effect magnitudes increased for jerk in the late drive, maximum negative drive, and peak drive acceleration across all boat classes, and in some boat classes for jerk in the early-to-mid-drive and the late recovery, first peak and finish dip acceleration (as shown in Figure 7.4 and Supplementary Table 9). Effect magnitudes decreased after adjustment for stroke rate for recovery peak acceleration in all boat classes, and for jerk in the early drive, the early recovery and the late recovery in some boat classes (refer to Figure 7.4 and Supplementary Table 9). Positive effects for peak drive acceleration, and negative effects for jerk in the late drive and maximum negative drive acceleration were decisively substantial in all boat classes. Positive effects for jerk in the early drive and the mid-drive, and first peak acceleration, and negative effects for jerk in the early-to-mid-drive) and the late recovery were decisively substantial in some boat classes (those with 90% compatibility intervals entirely in substantial values in Figure 7.4). Measures where the effects had adequate precision but were only possibly or likely substantial include positive effects in some boat classes for jerk in the early recovery and first peak acceleration, and negative effects in some boat classes for jerk in early-to-mid-drive and the late recovery, first dip and finish dip acceleration (those with more than half of the 90% compatibility intervals overlapping substantial values in Figure 7.4). Precision was inadequate (the superiority and inferiority hypothesis were not rejected, p_+ and p_- >0.05) in most boat classes for jerk in the early recovery, first dip and peak recovery acceleration.

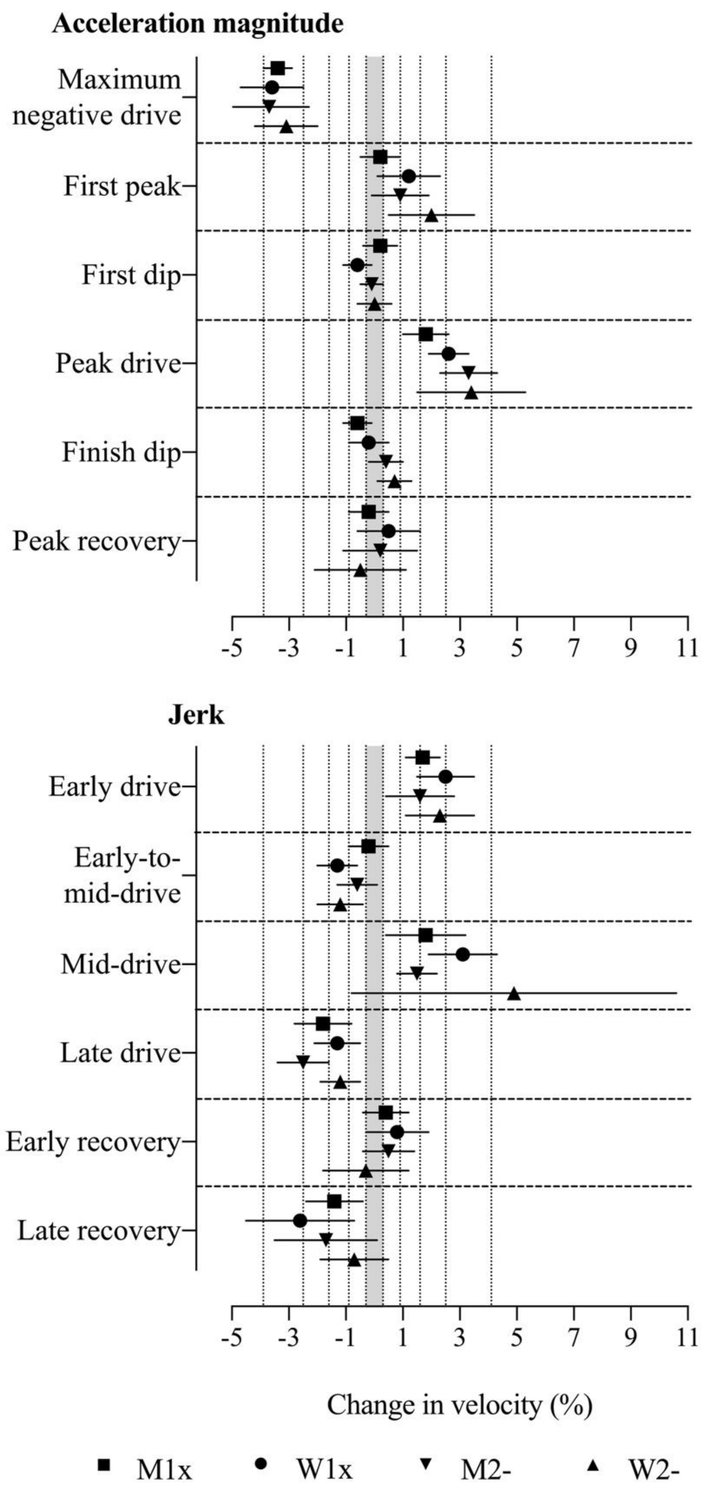

Figure 7.4 Change in boat velocity for a change in predictor variables of two within-crew standard deviations with adjustment for stroke rate. Data are mean (%) and 90% compatibility intervals. The shaded grey area covers trivial values (values within the smallest substantial change thresholds, -0.3 to 0.3%). Vertical dotted lines delineate threshold magnitudes of small (±0.3), moderate (±0.9), large (±1.6), very large (±2.5), and extremely large (4.1, -3.9%). Effects with compatibility intervals that do not enter the grey area are decisively (very likely or most likely) substantial. Effects with compatibility intervals that end within the grey area have adequate precision (possibly or likely substantial or trivial).

The adjustment of power and stroke rate reduced the magnitudes of most effects to the ranges of trivial to moderate (Figure 7.5 and Supplementary Table 10). Negative effects for maximum negative drive acceleration were decisively substantial in all boat classes. Positive effects for jerk in the early drive and the mid-drive, and peak drive acceleration, and negative effects for jerk in the late drive and the late recovery were decisively substantial in some boat classes (those with 90% compatibility intervals entirely in substantial values in Figure 7.5). Measures where the effects had adequate precision but were only possibly or likely substantial, include positive effects in some boat classes for jerk in the early drive, the mid-drive and the early recovery, first peak and peak drive acceleration, and negative effects in some boat classes for jerk in the early-to-mid-drive, the late drive and the late recovery, first dip and peak recovery acceleration (those with more than half of the 90% compatibility intervals overlapping substantial values in Figure 7.5). First dip acceleration in men's pairs was the only decisively trivial effect. Trivial observed effects that had adequate precision, where the true magnitudes were possibly or likely trivial were found in some boat classes for jerk in the early-to-mid-drive, first peak, first dip, and finish dip acceleration (those with less than half of the 90% compatibility intervals overlapping substantial values in Figure 7.5).

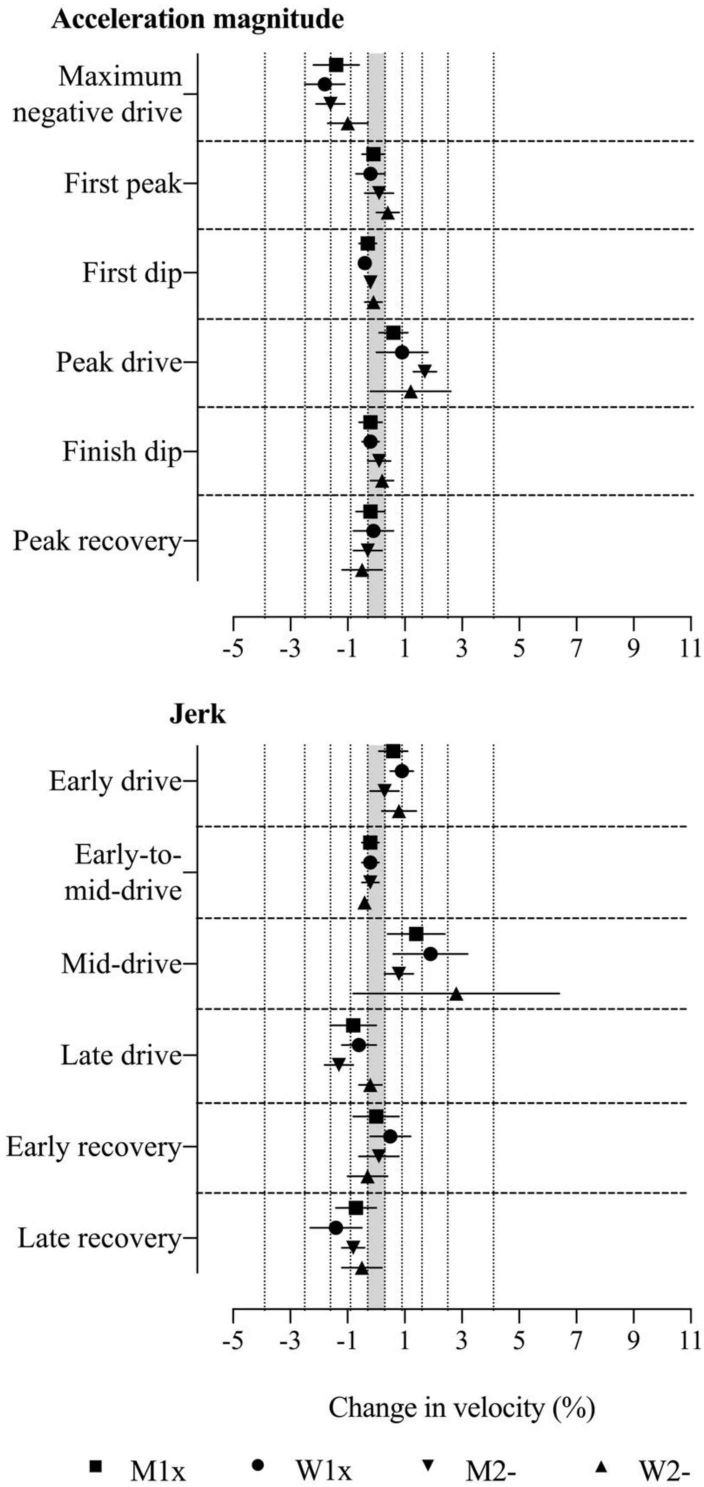

Figure 7.5 Change in boat velocity for a change in predictor variables of two within-crew standard deviations with adjustment for power output and stroke rate. Data are mean (%) and 90% compatibility intervals. The shaded grey area covers trivial values (values within the smallest substantial change thresholds, -0.3 to 0.3%). Vertical dotted lines delineate threshold magnitudes of small (±0.3%), moderate (±0.9%), large (±1.6%), very large (±2.5%), and extremely large (4.1, -3.9%). Effects with compatibility intervals that do not enter the grey area are decisively (very likely or most likely) substantial. Effects with compatibility intervals that end within the grey area have adequate precision (possibly or likely substantial or trivial).

Between-crew differences in the effect of predictor variables on velocity before adjustment were mostly moderate to very large in magnitude across all boat classes and were decisively substantial for most predictors in men’s singles, and for some predictors in women’s singles (refer to Supplementary Table 11). Precision was inadequate for between-crew differences in most predictors for men’s and women’s pairs. With adjustment for stroke rate (Supplementary Table 12) between-crew differences increased in magnitude to the range of large to extremely large, with decisively substantial differences observed for all predictors in men’s and women’s singles and for most predictors in men’s pairs. Precision remained inadequate for between-crew differences in most predictors for women’s pairs (refer to Supplementary Table 12). After adjustment for stroke rate and power (Figure 7.6 and Supplementary Table 13) between-crew differences were of similar magnitude and precision as those before adjustment, as described above and in Supplementary Table 11.

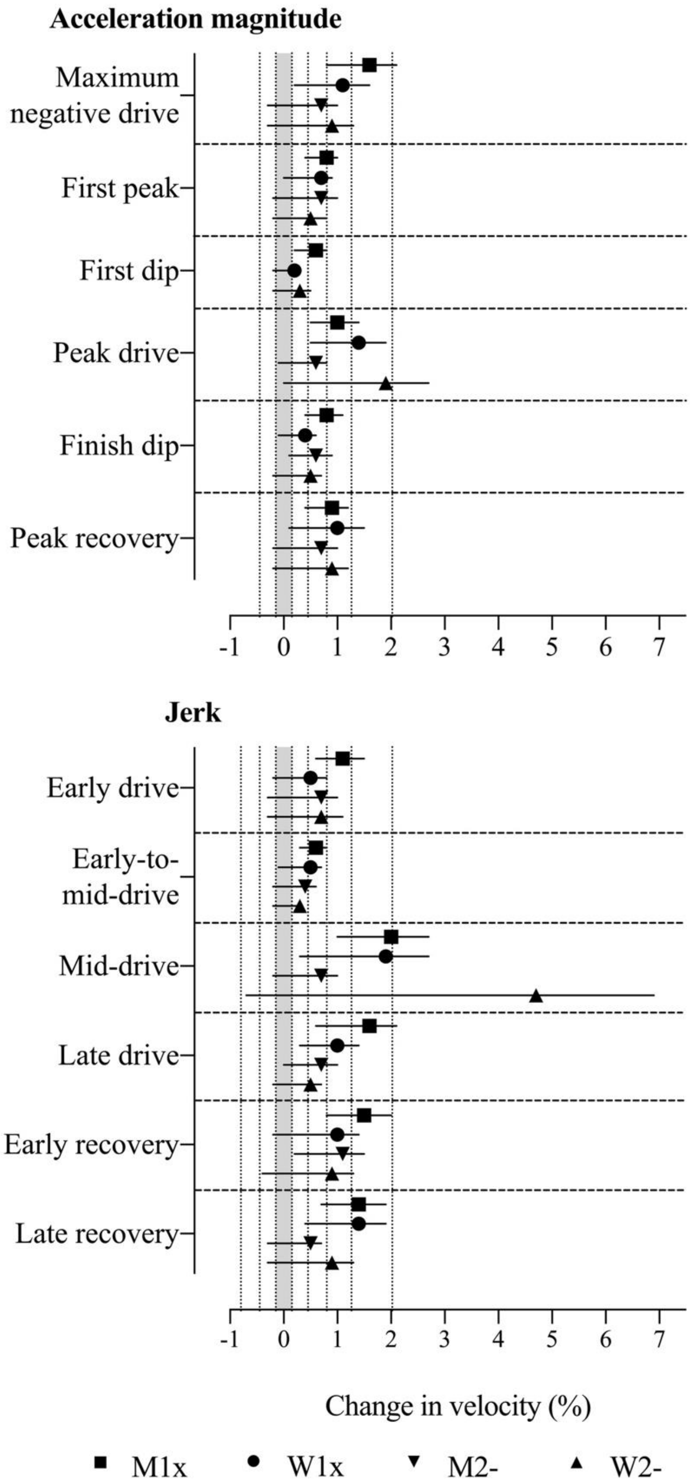

Figure 7.6 Differences between crews in the effects of the predictor variables with adjustment for power output and stroke rate. Data are SD (%) and 90% compatibility intervals. The shaded grey area covers trivial values (values within the smallest substantial difference thresholds, -0.15 to 0.15%). Vertical dotted lines delineate threshold magnitudes of small (±0.15), moderate (±0.45), large (+0.80), very large (+1.3), and extremely large (+2.0). Effects with compatibility intervals that do not enter the grey area are decisively (very likely or most likely) substantial. Effects with compatibility intervals that end within the grey area have adequate precision (possibly or likely substantial or trivial).

7.5 Discussion

Boat acceleration profiles are commonly used to provide feedback on rowing technique; however, current interpretation of acceleration profiles is largely informed by experiential knowledge given research in this area is limited to the drive phase and findings are conflicting. This investigation of relationships with performance for variables describing the boat acceleration profile provides empirical evidence for the evaluation of acceleration profiles in rowing. In this study, six variables of acceleration and jerk per stroke were assessed in relation to boat velocity during 2000-m racing in singles and pairs. Decisively substantial effects observed in all boat classes for maximum negative drive and peak drive acceleration, and for jerk in the early drive, the mid-drive (excluding women's pairs), and the late drive after adjustment for stroke rate reveal aspects of the acceleration profile relating to performance. Effect magnitudes were reduced after adjustment for stroke rate and power in most variables, illustrating their mediating effect on measures of boat acceleration.

The adjustment of stroke rate was required given its effect on boat acceleration (Kleshnev, 1998, 2010a), but also to provide insight into potential strategies for improving performance beyond increasing stroke rate. Effect magnitudes either increased or decreased after adjustment for stroke rate, depending on the predictor assessed. The increased effect magnitudes observed for maximum negative drive and peak drive acceleration, and jerk in the late drive likely reflect the effect of force applied during the drive on boat acceleration, given the strong relationship (R^2=0.904) between the force curve and boat acceleration profile during the drive phase (Draper & Smith, 2006). Faster rower COM velocities during the drive would likely improve force application (via higher oar angular velocities) and therefore peak drive acceleration, however, the adjustment for stroke rate can be expected to also account for the effect of oar angular velocity on force production, and therefore would not contribute to the increased effect magnitudes for peak drive acceleration with adjustment for stroke rate. Reduced effect magnitudes when adjusted for stroke rate describe the mediating effect of stroke rate on peak recovery acceleration and jerk in the early drive, the early recovery and the late recovery, whereby higher stroke rates increase the magnitudes of these variables. The mediating effect of stroke rate is likely related to faster rower COM movement during the recovery, given most of these variables occurred during the recovery phase, and increased stroke rate is largely achieved via shorter recovery phase duration (Dawson, Lockwood, Wilson, & Freeman, 1998; Held et al., 2020).

Relationships between the acceleration measures assessed and boat velocity with adjustment for both power and stroke rate may provide the most meaningful practical impact for coaches and sport scientists in the interpretation of acceleration profiles (those effects presented in Figure 7.5 and Supplementary Table 10), as the effects on velocity are not attributable to the power applied or the stroke rate performed, but rather reflect additional performance improvements. The adjustment for power output informs measures of acceleration associated with enhancements in rowing velocity for the same given power output. Specifically, greater maximum negative drive acceleration, greater positive peak drive acceleration, greater jerk in the early and mid-drive, and more negative jerk in the late drive and late recovery phases are measures associated with further benefits to performance. Moreover, the large to very large effect magnitudes for both stroke rate and power on boat velocity established in Chapter Six demonstrate the need for the adjustment of both stroke rate and power output when assessing relationships between biomechanical variables and velocity. The additional adjustment for power with adjustment for stroke rate reduced effect magnitudes resulting in the loss of precision for many effects, revealing the mediating effect of power output on most of the variables assessed. The reduction of effect magnitudes after the additional adjustment for power for jerk in the late drive, maximum negative drive acceleration, and peak drive acceleration suggest that the effects observed for these variables prior to the adjustment for power simply reflect the positive relationship between power and velocity, whereby faster velocities associated with greater magnitudes of these variables are explained by higher power outputs.

The negative effects for maximum negative drive acceleration and jerk in the late recovery after adjustment for stroke rate, and adjustment for stroke rate and power, illustrate the transition from late recovery to the catch and early drive phases of the rowing stroke as having an important association with velocity. The late recovery, catch and early drive phases of the stroke require highly technical movement coordination occurring over a very short time period (approximately 0.4 s at a stroke rate of 32 min^{-1}), consisting of rower COM change of direction, blade placement and force application (Kleshnev, 2010a). Although rower COM acceleration and force applied at the footplate were not assessed in the current study, the negative effects for jerk in the late recovery may relate to a delayed negative acceleration of rower COM in the late recovery, requiring greater resultant sternward directed force at the footplate over a shorter time period. A larger resultant force at the footplate applied over a shorter time period can be expected to correspond to greater (i.e., less positive) maximum negative drive accelerations occurring with effective blade placement at the catch. An advantageous performance effect of delayed negative acceleration of rower COM during the recovery has not been investigated, however has been implemented by elite rowers and coaches (Bond, Murray, & Stevenson, 2016; personal observations). An example of this includes the finish pause adopted by many international crews at low stroke rates, which encourages rowers to move with the boat on the recovery, rather than slowing themselves down into the front turn. However, further research investigating relationships between maximum negative drive acceleration, jerk between peak recovery acceleration and maximum negative drive acceleration, force applied at the footplate, and rower COM acceleration during the recovery phase is required to confirm any effect on performance of delayed negative acceleration of rower COM during the recovery.

The positive effects for first peak and peak drive acceleration, and jerk in the early drive and the mid-drive after adjustment for stroke rate, and for most of these variables after adjustment for stroke rate and power, likely relate to force application during the drive phase. The boat acceleration profile during the drive phase reflects force curve shape (Draper & Smith, 2006), with force application during the drive demonstrating extremely large positive relationships with rowing performance (Chapter Six). The positive effects for jerk in the early drive and the mid-drive may reflect rate of force development, which has a positive relationship with rowing performance (Warmenhoven, Cobley, et al., 2017) and is proposed to increase the impulse and subsequent boat velocity achieved (Hume, 2018; Millward, 1987). Therefore, enhanced propulsive force application during the drive is expected to result in the achievement of higher first peak and peak drive acceleration, and increased jerk in the early drive and in the mid-drive.

The between-crew differences in predictors after adjustment for stroke rate, demonstrate the crew-specific nature of relationships between velocity and measures of boat acceleration. For predictors with adequate precision in both their mean effect and between-crew differences, a change in the predictor is expected to be associated with a change in performance in the same direction in most crews, however, is best investigated on an individual basis to determine the magnitude of the association for a specific crew. As such, individual-based analyses can reveal areas of the boat acceleration profile associated with improved performance in a particular crew that are not evident from the mean effects for the cohort assessed. The random effect solutions for crew identity in the current model present differences from the mean modifying effect for each crew, allowing the assessment of crew-specific relationships, and therefore the provision of individualised feedback on boat acceleration profiles.

7.5.1 Practical Applications

- Stroke rate and power have mediating effects on most measures of boat acceleration and jerk and should be considered when assessing the boat acceleration profile.

- Greater (i.e., less positive) maximum negative drive accelerations and greater jerk in the late recovery are associated with faster velocities, revealing the late recovery as an important area for technical focus.

- Improved performance is also associated with greater peak drive acceleration, and jerk in the early drive and the mid-drive, likely reflecting force application during the drive.

- Relationships between some measures of the boat acceleration profile and velocity differ between crews and are best assessed on an individual basis.

7.6 Conclusion

Greater maximum negative drive accelerations and greater jerk in the late recovery are related to faster velocities, likely reflecting delayed rower centre-of-mass negative acceleration in preparation for the catch. Peak drive and first peak accelerations, and jerk between the first dip in acceleration during the drive and peak drive acceleration are associated with improved performance, likely reflecting propulsive force during the drive. Practitioners should consider accounting for differences in power output and stroke rate (such as statistically or during the collection of data) when assessing boat acceleration profiles in rowing due to the mediating effect of these variables.

Chapter Eight: Overall Discussion

Knowledge of the factors contributing to boat velocity and a valid system for their measurement are necessary for effective and targeted improvements in rowing performance and its repeated assessment. Therefore, the overarching aim of this thesis was to extend the current knowledge regarding the validity of commercially available rowing instrumentation systems, and their use in identifying the key components of rowing performance. The five studies presented in this thesis were undertaken in response to the gaps in knowledge identified in the literature review, which included the validity of catch and finish oar angle and power measures from commercially available rowing instrumentation systems, and the use of these devices in assessing the components of rowing performance. The studies within this thesis were also shaped to address the needs of coaches and sport scientists in providing technical feedback and the interpretation of boat acceleration profiles. As such, valuable practical applications were derived from the key findings of this thesis and can be used to inform the assessment of measures of rowing performance by coaches, sport scientists, and athletes. This chapter will outline the key practical applications from the findings of this thesis and discuss the wider applications of instrumentation systems within rowing, including future research directions. Finally, consideration of the limitations of this thesis are presented.

8.1 Practical applications

The studies conducted in this thesis were directed by coach-driven research questions, with the objective of informing coach and sport scientist practice in regard to the use of rowing instrumentation systems and the assessment of rowing technique. As such, a number of research outcomes can be applied by coaches and sport scientists in their practice, as listed in the following subsections.

8.1.1 Validity of rowing instrumentation systems

Peach devices have reasonable validity for measures of catch angle, finish angle and arc angle on a stroke-to-stroke basis, given the ~0.4° random error estimates established in Chapter Three. However, the assessment of mean angle over 30-1000 strokes is recommended when using EmPower due to its high random error estimates (0.8 to 11.6°), but reasonable systematic error estimates (<1°). For both Peach and EmPower, use of the same unit is recommended when conducting repeated gate angle assessments, due to the ~0.3 to 1° (Peach) and ~1 to 2° (EmPower) between-unit differences observed in systematic error.

For measures of power output, practitioners should be aware that power output as measured by Peach, EmPower, Weba and the Concept 2 is likely lower than that performed by the rower, as observed in Chapter Four. This is particularly evident for EmPower in all stages, and for Peach and EmPower at very high power outputs. Use of the same device and unit is recommended for repeated measurements of power or the comparison of power between rowers, due to the between-device and potential between-unit differences in mean power observed. The differences from the Concept 2 in mean power for the Peach, Weba, and EmPower can be used to estimate on and off-water power differences, for which most appear to be related to a reduction in the power applied on-water (likely reflecting the greater technical demand of on-water rowing) rather than device error. Peach can be used with confidence for assessments of stroke-to-stroke power and of relationships between power and rowing performance, given its adequate measurement sensitivity. Weba and EmPower are best used to assess mean power rather than stroke-to-stroke measures of power due to the noise in the signal output of these devices, which can provide unreliable or misleading information for individual strokes and would attenuate relationships with rowing performance. The Concept 2 is also best used to assess mean power rather than stroke-to-stroke measures due to its lack of measurement sensitivity (apparent smoothing) and negative error in the first ~5 strokes, which would produce a small attenuation of relationships between power and rowing performance where power is a predictor.

8.1.2 Prediction of race performance

The ability to predict 2000-m on-water race performance with less than 0.6 % error in singles and coxless pairs with the analysis methods used in Chapter Five, enables quantification of the performance gap between current and target on-water race performances. Current practice typically involves assessment of a crew's training and race performances as a prognostic, which is the percentage difference in boat velocity relative to that for the World's best time for a specific boat class. Monitoring prognostics are used to provide an indication as to how well a crew is tracking in comparison to the World's best time. The coefficients for power, stroke rate and technical efficiency established in Chapter Five enable estimation of the performance gap in more detail than that with prognostics, providing a means for determining the power output and stroke rate required to achieve any given race time when environmental conditions effect all crews in a given race equally. The differing contributions of power, stroke rate, and technical efficiency to race performance between crews (established in the analysis in Chapter Five) can be used to identify crew-specific areas for performance improvement when assessed individually. Power output and stroke rate (albeit to a lesser extent) are both areas where substantial improvements in 2000-m on-water rowing performance can be made. Knowledge of power and stroke rate targets from estimation of the performance gap for these variables can be used to inform targeted training strategies, such as the prescription of target power outputs and stroke rates for key on-water sessions that align with race performance goals.

8.1.3 Technical analysis in rowing

The relationship between individual measures of rowing technique and boat acceleration with rowing velocity in Chapters Six and Seven highlight the aspects of rowing technique coaches and sport scientists should look for when observing rowers and can be used to inform the focus of training interventions targeted at improving performance. Rower force development should be prioritised as a key component of power output and boat velocity, including earlier occurrences of peak force within the stroke, and the reduction of catch and finish slips targeted. The achievement of greater catch angles is also beneficial to rowing performance, and likely improve velocity via the improved mechanical efficiency associated with lift forces at the catch. For the evaluation of boat acceleration profiles, greater positive acceleration and jerk during the drive are associated with improved performance, likely reflecting greater and earlier force application during the drive. Greater maximal negative drive acceleration and greater jerk in the late recovery were also associated with improved performance, highlighting the movement of rowers in the late recovery, blade placement and force application at the catch as important areas for technical coaching focus. Relationships with rowing performance for mean and peak force, arc and catch angle, maximum negative drive acceleration, and jerk in the mid-drive and late recovery were variable between crews in some boat classes and are therefore best assessed on an individual basis to determine crew-specific opportunities for performance improvement. Stroke rate and power output have mediating effects on many of the measures of rowing technique and boat acceleration assessed, and their adjustment should be considered by practitioners when assessing these variables.

8.2 Future directions

8.2.1 Measuring rowing performance

Future research investigating biomechanical variables in rowing should consider the use of stroke-to-stroke data in analyses, as used in the Chapters Five, Six, and Seven. The analysis of stroke-to-stroke data allowed the variance introduced by differences in environmental conditions occurring within a race (e.g., wind gusts or water chop) to be partitioned out of the respective effect estimates, and likely improved the precision of the effects observed in Chapters Six and Seven due to the much larger sample sizes available in comparison to analyses of race means. The Peach PowerLine system was found to have acceptable reliability for the measurement of stroke-to-stroke oar angle and power data (Chapters Four and Five) and can be used for the evaluation of rowing catch, finish, arc angles, and power measures on a stroke-by-stroke basis.

Research investigating relationships between measures of gate angle or power with rowing performance should consider the attenuation effects established for these variables in Chapters Three and Four. A lack of measurement sensitivity or the introduction random error in the signal output of a given device, when assessing stroke-to-stroke data, will attenuate observed effects for power or gate angle measures and widen their compatibility limits, and therefore may misrepresent true effects for these variables (Hopkins et al., 2009). Peach had negligible attenuation of relationships with power and gate angle, and therefore can be used effectively when investigating effects associated with these variables. However, for relationships where power or gate angle are the predictor, the modification of effects would range from modest to considerable for EmPower and Weba (only power assessed), limiting the ability to detect the true modifying effect of power or gate angle on a dependent variable when using these devices. Given the random error in the signal output of Weba and EmPower devices in the measurement of power per stroke, these devices are better suited for quantifying training and performance over a session (as power meters are typically used in cycling) rather than for stroke-to-stroke analyses.

Knowledge of the systematic error and random error associated with the measurement of power output by the devices tested in Chapter Four supports the use of rowing instrumentation systems as a training and competition monitoring and assessment tool. However, several barriers still exist to their implementation in daily practice, as experienced during the collection of data for the studies in this thesis. Whilst EmPower and Weba systems are simple to setup and use, there are considerable time demands associated with Peach setup, perhaps restricting the willingness of practitioners to use the Peach system. Time requirements for device set-up are compounded in training environments where crew and boat changes are frequent and using the same unit for a given crew (as recommended due to the between-unit differences established in Chapters Three and Four) becomes impractical. The de-rigging of boats to optimise boat storage space is not uncommon in rowing clubs and may reduce the feasibility of leaving instrumentation systems attached to boats for repeated use. The positive impact of rowing instrumentation systems may also be limited by the additional learning required by practitioners to set up the devices and interpret their data. Finally, investment in rowing instrumentation systems will not be a financially viable option for many rowing programs, with the cost to equip a boat ranging from ~$2,000 to ~$5,000 AUD for a single and ~$13,000 AUD for an eight.

The barriers associated with the implementation of rowing instrumentation systems in daily practice are unlikely to hinder their use in elite training environments. In comparison to typical club environments crew and boat changes are infrequent, daily de-rigging and re-rigging to manage boat storage is not a common occurrence, coaches and sport scientists usually have expertise in the use of rowing instrumentation systems and the interpretation of their data, and elite programs often have the resources to invest in such equipment. Despite the comprehensive benefits of rowing instrumentation systems to both technical and physiological assessment, it is likely their use by the wider (non-elite) rowing community will remain limited. Continued research and innovation in the area of on-water rowing power measurement is therefore needed to address these barriers and enable their widespread use in daily practice.

8.2.2 Assessment of rowing technique

Smallest important (substantial) change magnitudes can be derived for technical measures of rowing performance and measures of boat acceleration from the corresponding percentage change in boat velocity and the within-crew SDs presented in Chapters Six and Seven. Knowledge of smallest important change magnitudes for measures of rowing technique and boat acceleration are needed to determine whether the magnitude of a technical change is large enough to have a positive impact on boat velocity. As such, the smallest important change magnitudes for technical and boat acceleration variables should be utilised by practitioners when assessing changes in technical measures within a crew, or when comparing crews. The assessment of rowing technique relative to smallest important magnitudes can also be used to inform the efficacy of coaching practice in facilitating a desirable technical change, informing effective strategies for skill attainment in rowing.

Longitudinal monitoring of rowing technique and relationships between rowing technique and boat velocity, using the measures assessed in Chapter Six, can be used to establish the trajectory of technical improvements for rowers within the development pathway. Research investigating typical values for the technical variables assessed in Chapter Six in successful elite rowers could inform the establishment of technical benchmarks representative of the level of technical skill required for success at the elite level. Longitudinal monitoring of technical variables would enable the estimation of technical skill trajectories in development rowers, from which the time required for a given rower to achieve an elite standard of technical skill can be derived. This would enable the identification of technically proficient development rowers who may be more likely to achieve an elite standard of technical skill. Furthermore, the ability to quantify the gap in a rower's technical skill level from an established elite benchmark, and measure skill progression relative to the smallest important change magnitude (as established in Chapter Six) enables assessment of the efficacy of coaching and skill acquisition practice in improving technical ability.

The findings in Chapters Five, Six, and Seven can be used to inform the evaluation of rowing technique and other measures of rowing performance by coaches and sport scientists when working specifically with men's and women's singles and/or coxless pair boat classes. Given the reduction in power and changes in technical measures that occur between boat classes (Coker, 2010), the magnitude and direction of the relationships established for biomechanical variables in singles and pairs in this thesis may not generalise to other boat classes. Although research investigating factors effecting rowing performance rarely examine multiple boat classes, consider gender, or para boat classes (Coker, 2010; R. M. Smith & Draper, 2006; Warmenhoven, Cobley, et al., 2017), further research is needed to explore similarities and differences in relationships between biomechanical measures and performance in other boat classes.

8.2.3 Training programming and monitoring strategies

The estimation of power and stroke rate targets required to achieve a given race performance (Chapter Five), enhances the value of monitoring on-water power output in key high-intensity sessions by providing further insight into the current performance ability of a crew relative to race performance targets. For example, coaches can calculate the mean power required for a particular key session that corresponds to a target race performance from the percentage difference between current race and key session powers and the calculated power required for the target race performance. This would allow the coach to not only track the crew's performance in training relative to their goal race performance, but also estimate the increase in mean power required in the key training session to ensure the crew is on track to achieving their target race performance, without the need for repeated race performance assessment.

Rowing instrumentation systems may enable the accurate quantification of training load in rowing, when informed by the device error estimates established in Chapter Four. Current methods for quantifying training load in rowing predominantly assess internal load via time spent in heart rate zones (Guellich et al., 2009; Plews and Laursen, 2017; Tran et al., 2015; observed as common practice). However, inaccuracies can arise in the quantification of training load via heart rate due to the influence of multiple factors including altitude (Vogel, Hansen, & Harris, 1967), core temperature (González-Alonso, Mora-Rodríguez, Below, & Coyle, 1997) and hydration status (González-Alonso, Mora-Rodríguez, & Coyle, 2000), complicating the relationship between heart rate and exercise intensity. The effect of cardiac drift (the gradual increase in heart rate at a consistent power) during extended training durations below LT_1 (Hartwell, Volberding, & Brennan, 2015) and heart rate lag (the disproportionately gradual reduction in heart rate for an immediate reduction in power output) during repeated high-intensity intervals (Cerretelli & Di Prampero, 1971) contributes to the respective over- and underestimation of time in target training zones at low and high intensities in highly trained cyclists (Nimmerichter et al., 2011; Vogt et al., 2006), and flatwater kayaking (Hogan, Binnie, Doyle, Lester, &

Peeling, 2020). The quantification of external training load via measures of power output from rowing instrumentation systems, as power meters are habitually used in cycling (Allen & Coggan, 2012), provides an absolute measure of the training performed and is assessed independently of environmental conditions, heart rate lag, or cardiac drift (Halson, 2014). Additional research is first needed to explore the use of rowing instrumentation systems in establishing on-water rowing training zones via on-water step testing. A valid method of establishing on-water specific training zones would then allow the quantification of external training load specific to on-water training, which comprises the majority of training volume in rowers (Plews & Laursen, 2017). The quantification of external training load from power-based training zones established during on-water step testing has been accomplished in flatwater kayak (Hogan et al., 2020; Winchcombe, Binnie, Doyle, Hogan, & Peeling, 2019), and therefore may be feasible in rowing.

Chapters Five and Six revealed stroke rate as an area where large improvements in rowing performance can be attained. An upper limit to the relationship between stroke rate and performance was not identified in this thesis, whereby it appears enhancements in performance can be attained even at very high stroke rates. This is supported by the findings of Held et al. (2020) who did not find an optimal stroke rate for the production of power output in rowing, and by the trend for higher stroke rates observed in international rowing in recent years. The development of a crew’s capacity to maintain high stroke rates during racing is therefore an advantageous focus of training and may include the prescription of high stroke rate work, and a focus on developing rate of force development in strength training (which would also support the earlier achievement of peak force during the drive, which was found in Chapter Six to benefit performance). Training strategies targeting high stroke rates differ from those typically employed in rowing, whereby the majority of training is performed at low stroke rates (~20 strokes·min^{-1}), with high-intensity sessions often failing to reach race rates (Fiskerstrand & Seiler, 2004; personal observations). Prescribing high stroke rates (above target race rates) for high-intensity training sessions may improve a crew’s ability to maintain higher stroke rates during racing, relating to reductions in perceived effort and improved metabolic efficiency, as occurs in cyclists following high-cadence training (Whitty, Murphy, Coutts, & Watsford, 2016). Additionally, the prescription of high stroke rates in high-intensity training sessions would provide an opportunity for the development of technical skill at race-specific stroke rates, with improved measures of rowing technique further increasing power output, as demonstrated in Chapter Six.

8.3 Limitations of the research

The following limitations should be considered in the interpretation of findings from this thesis:

- Undetected rotation of the Peach unit baseplates may have introduced errors of ~0.5° to the random error estimates for Peach angle measurement in Chapter Three. Although inspection of baseplate position after each trial and the analysis of residuals removed any obvious data outliers relating to possible baseplate rotation, small undetected rotations may have been present in the data. However, any undetected rotations were within the range of the smallest important change in angle, and therefore would not affect acceptable validity outcome for Peach devices. Further, it is possible baseplate rotation that is not visually obvious may occur in the field and therefore contribute to random errors of similar magnitude in practice.

- The reasonably small number of Peach and EmPower units tested in Chapter Three contribute to the uncertainty in between-unit systematic error differences. Due to device cost, additional Peach and EmPower units could not be purchased for assessment, and although six Peach units were tested, three were excluded from analyses due to identification of baseplate rotation. Nevertheless, it is common for studies investigating the validity of instrumentation systems to only assess one unit per device (Abbiss et al., 2009; Bertucci et al., 2005; Sparks et al., 2015), whereby the between-unit systematic error difference for a device is often not established. Between-unit systematic error differences established in Chapters Three and Four inform practitioners of the additional error any given device off the shelf may have, and therefore are a valuable to practitioners, despite their uncertainties.

- The extent to which device differences in mean power from the instrumentation in Chapter Four represent device systematic error or error introduced by the instrumentation is not known. Although systematic error estimates for the Concept 2 are similar to those established elsewhere (Boyas et al., 2006), error may have been introduced for the instrumentation relating to the location of force and displacement measurement and the correction for force relative to oar angle. Therefore, future research comparing measures of power derived from force and displacement at the same location as those by the devices being assessed is warranted to determine if systematic error magnitudes are similar.

- The prediction of race performance in Chapter Five could be criticised for predicting the performance of races for which the stroke velocity was used to determine measures that were included in the multiple linear regression analyses. Further research investigating the prediction of performances other than those used to derive the coefficients in Table 5.4 would further support the validity of the prediction model.

- Given the separate analyses of predictors in Chapters Six and Seven, some effects can be expected to represent underlying relationships between predictors. As such, a change in one predictor likely contributes to changes in others and therefore the effects will not have a purely additive effect on performance. Rather, the results present the extent to which predictors are associated with a change in velocity, informing the separate assessment of these variables by practitioners, with the adjustment for power and stroke identifying predictors mediated by these variables.

- Non-final races were included in the analyses for Chapters Five, Six and Seven where crews may have implemented sub-maximal pacing strategies. However, as these studies involved the assessment of stroke data, variations in measures between strokes due to changes in pacing strategy would improve the precision of estimates for the relationship of measures with performance.

8.4 Conclusion

The findings presented in this thesis inform the validity of rowing instrumentation systems for measures of oar angle and power output and advise factors contributing to performance in rowing and their evaluation by coaches and sport scientists, directing effective and targeted training strategies. The Peach PowerLine system is an acceptably reliable tool for the stroke-to-stroke measurement of oar angle and power output in rowing and can be used to quantify rowing technique. On-water rowing race performance can be predicted with reasonable accuracy from measures derived from rowing instrumentation systems in small boat classes. Power output, stroke rate and force production are key factors contributing to rowing performance and should be targeted for performance improvements. The association with performance for catch angle is evident with adjustment for stroke rate and power, reflecting the mechanical efficiency at the catch. Greater maximal negative boat acceleration and jerk in the late recovery and greater positive boat acceleration and jerk in the early-to-mid drive phases illustrate favorable acceleration profiles with respect to performance. The research conducted herein promotes the wider applications of rowing instrumentation systems for the analysis and assessment of additional factors contributing to rowing performance outcomes, determining the efficacy of technical coaching practices, external training load monitoring on-water, and the shaping of training prescription to meet power and stroke rate race targets. In summary, the findings presented in this thesis extend the body of knowledge regarding performance assessment in rowing and provide real-world applications for the interpretation of technical analysis measures and the prediction of on-water race performances.

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Appendices

Appendix A: Supplementary tables

Supplementary Table 1. Differences or changes in race velocity for a 2-SD change in predictors that were included in multiple linear regressions in the four boat classes, as illustrated in Figure 5.1. Data are mean (%) for predictors, with ± 90%CL, with observed magnitude and p values for non-inferiority and non-superiority tests (p–/p+).

	Single sculls		Coxless pairs	
	Men (M1x)	Women (W1x)	Men (M2-)[a]	Women (W2-)
Mean race power	**5.6, ±0.7; e.large****** <0.001/>0.999	**6.6, ±1.2; e.large****** <0.001/>0.999	—	**6.0, ±1.1; e.large****** <0.001/>0.999
Mean stroke rate	**1.1, ±0.4; mod****** <0.001/0.997	0.9, ±0.8; small* 0.01/0.90	—	1.7, ±2.1; large 0.06/0.88
Mean headwind	**-2.2, ±0.5 large****** >0.999/<0.001	**-4.7, ±1.5 e.large****** 0.999/<0.001	—	-3.0, ±2.3 v.large*** 0.97/0.02
Technical efficiency	5.1, ±3.8; e.large 0.05/0.95	0.0[a]; trivial —[b]	—	1.9, ±2.2; large 0.15/0.84
Race conditions	2.9, ±2.0; v.large** 0.04/0.95	4.2, ±1.8; e.large*** 0.01/0.99	—	1.0, ±1.0; mod 0.08/0.88
Stroke-velocity variability	-0.2, ±0.5; trivial[0]* 0.34/0.04	0.6, ±1.3; small 0.11/0.68	—	0.2, ±1.3; trivial 0.21/0.46

M1x, men's single scull; W1x, women's single scull; M2-, men's coxless pairs; W2- women's coxless pairs.
Number of crews are shown in Table 5.1.
[a]Insufficient data for analysis (five races for six predictors).
[b]Indicates negative estimate probably due to sampling variation, so estimated as 0 and therefore no CL and $p_{–}/p_{+}$.
Scale of magnitudes: <0.3%, trivial; ≥0.3%, small; ≥0.9%, moderate (mod); ≥1.6%, large; ≥2.5%, very large (v.large); ≤-3.9, ≥4.1%, extremely large (e.large).
Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely, ****most likely.
*** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005 respectively).
Reference-Bayesian likelihoods of trivial change: [0]possibly; [00]likely; [000]very likely, [0000]most likely.
Likelihoods are not shown for effects with inadequate precision at the 90% level (failure to reject any hypotheses: p>0.05).
Effects in **bold** have adequate precision at the 99% level (p<0.005).

Supplementary Table 2. Change in boat velocity for a change in predictor variables of two within-crew standard deviations without adjustment in the four boat classes. Data are mean (%), ±90% compatibility limits, with observed magnitudes and p values for non-inferiority and non-superiority tests ($p_{–}/p_{+}$).

	M1x	W1x	M2-	W2-
Time and velocity variables				
Stroke rate	**7.0, ±2.1; e.large****** <0.001/>0.999	**7.6, ±0.8; e.large****** <0.001/>0.999	**8.6, ±2.7; e.large***** 0.005/0.996	**9.0, ±1.2; e.large****** <0.001/>0.999
Within-stroke velocity range	**6.5, ±1.4; e.large****** <0.001/>0.999	**7.1, ±0.7; e.large****** <0.001/>0.999	7.2, ±3.9; e.large*** 0.01/0.98	**9.0, ±0.9; e.large****** <0.001/>0.999
Time from catch to minimum velocity	**-6.5, ±3.5; e.large***** 0.996/0.004	**-4.0, ±3.0; v.large****** >0.999/<0.001	-4.0, ±3.0; v.large*** 0.96/0.03	-5.0, ±3.6; e.large*** 0.98/0.02
Distance per stroke	0.9, ±1.7; mod 0.10/0.75	0.1, ±2.5; trivial 0.39/0.44	2.9, ±5.7; v.large 0.12/0.85	0.0, ±3.4; trivial 0.42/0.44
Force variables				
Power output	**7.1, ±0.8; e.large****** <0.001/>0.999	**7.8, ±0.3; e.large****** <0.001/>0.999	**8.9, ±1.2; e.large****** 0.001/0.999	**9.5, ±1.8; e.large****** <0.001/>0.999
Mean force	**8.2, ±1.3; e.large****** <0.001/>0.999	**9.2, ±1.0; e.large****** <0.001/>0.999	**9.1, ±2.8; e.large****** 0.002/0.998	**13.3, ±5.4; e.large***** 0.001/0.999
Peak force	**7.4, ±1.4; e.large****** <0.001/>0.999	**9.6, ±1.5; e.large****** <0.001/>0.999	8.1, ±4.2; e.large*** 0.007/0.99	**13.4, ±6.5; e.large****** 0.003/0.997
Rate of force development	**3.0, ±0.8; v.large****** <0.001/>0.999	**3.1, ±0.8; v.large****** <0.001/>0.999	3.7, ±2.8; v.large*** 0.02/0.97	**4.7, ±1.3; e.large****** <0.001/>0.999
Time to peak force from the catch	**-2.4, ±0.8; large****** >0.999/<0.001	**-3.2, ±2.3; v.large****** 0.999/<0.001	-3.0, ±2.5; v.large*** 0.96/0.03	**-4.4, ±2.0; e.large****** 0.998/0.001
Mean-to-peak force ratio	**-2.5, ±0.7; v.large****** >0.999/<0.001	-1.2, ±0.9; mod** 0.95/0.006	-3.6, ±1.9; v.large*** 0.99/0.007	-2.1, ±2.1; large** 0.92/0.04
Peak force angle	0.8, ±1.0; small** 0.03/0.81	0.5, ±1.4; small 0.16/0.61	1.6, ±1.4; large** 0.03/0.94	0.9, ±2.1; mod 0.15/0.71
Oar angle variables				

Catch slip	**-2.9, ±0.8; v.large****** >0.999/<0.001	**-4.7, ±1.3; e.large****** >0.999/<0.001	**-3.6, ±1.1; v.large****** 0.998/0.001	-1.0, ±8.7; mod 0.56/0.39
Finish slip	**-2.7, ±0.6; v.large****** >0.999/<0.001	**-5.0, ±1.1; e.large****** >0.999/<0.001	-3.5, ±2.7; v.large*** 0.97/0.03	-4.8, ±2.8; e.large*** 0.99/0.005
Finish angle	**-1.4, ±0.9; mod***** 0.98/0.002	-1.6, ±1.4; large** 0.94/0.02	1.2, ±15.8; mod 0.41/0.56	-5.7, ±5.3; e.large** 0.95/0.04
Arc angle	-1.6, ±1.1; large*** 0.98/0.004	-1.3, ±1.1; mod** 0.93/0.01	1.8, ±2.6; large 0.08/0.87	-6.0, ±8.0; e.large 0.89/0.09
Catch angle	0.9, ±1.2; mod 0.05/0.80	0.0, ±0.9; trivial 0.27/0.31	-4.2, ±2.6; e.large*** 0.98/0.01	3.9, ±6.6; v.large 0.12/0.85

M1x, men's single scull; W1x, women's single scull; M2-, men's coxless pairs; W2- women's coxless pairs.
Number of crews: 10, 8, 3 and 6 respectively.
Number of races: 17, 13, 5, 12 respectively.
Scale of magnitudes: <0.3%, trivial; 0.3-0.9%, small; 0.9-1.6%, moderate (mod); 1.6-2.5%, large; 2.5-4.1%, very large (v.large); >4.1%, extremely large (e.large).
Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely, ****most likely.
*** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005 respectively).
Reference-Bayesian likelihoods of trivial change: ^{0}possibly; ^{00}likely; ^{000}very likely, ^{0000}most likely.
Likelihoods are not shown for effects that are unclear at the 90% level (failure to reject any hypotheses: p>0.05).
Effects in **bold** have adequate precision at the 99% level (p<0.005).

Supplementary Table 3. Change in boat velocity for a change in predictor variables of two within-crew standard deviations with adjustment for power output in the four boat classes. Data are mean (%), ±90% compatibility limits, with observed magnitude and p values for non-inferiority and non-superiority tests (p_{-}/p_{+}).

	M1x	W1x	M2-	W2-
Time and velocity variables				
Stroke rate	**2.5, ±1.3;** **v.large***** 0.002/0.99	**2.1, ±0.8;** **large****** <0.001/0.998	**3.5, ±0.4;** **v.large****** <0.001/>0.999	**2.5, ±1.0;** **v.large****** 0.001/0.997
Within-stroke velocity range	0.4, ±0.4; small** 0.01/0.67	0.0, ±0.6; trivial 0.16/0.22	0.3, ±1.5; small 0.14/0.48	1.1, ±0.8; mod** 0.01/0.95
Time from catch to minimum velocity	-0.6, ±0.8; small* 0.73/0.04	-0.4, ±0.4; small*^{0} 0.63/0.01	-0.3, ±1.1; small 0.55/0.09	-0.4, ±0.5; small* 0.75/0.04
Distance per stroke	**2.7, ±1.1;** **v.large****** <0.001/0.999	**2.3, ±1.2;** **large***** 0.002/0.99	2.1, ±2.8; large 0.06/0.92	1.5, ±1.1; v.large*** 0.01/0.96
Force variables				
Mean force	**-3.0, ±1.4;** **v.large****** 0.998/<0.001	**-4.1, ±1.2;** **e.large****** 0.999/<0.001	**-4.9, ±1.4;** **e.large***** 0.998/<0.001	-3.7, ±2.7; v.large*** 0.94/0.01
Peak force	**-2.2, ±0.9;** **large****** 0.995/<0.001	**-2.5, ±0.7;** **v.large****** >0.999/>0.001	-3.8, ±2.0; v.large*** 0.98/0.009	**-3.0, ±1.8;** **v.large***** 0.99/0.004
Rate of force development	-0.3, ±0.4; small*^{0} 0.46/0.006	**-0.2, ±0.2;** **trivial^{00}** 0.23/0.002	-0.1, ±0.6; trivial 0.22/0.10	0.3, ±0.5; small*^{0} 0.02/0.10
Time to peak force from the catch	**-0.5, ±0.3;** **small**** 0.91/<0.001	**-0.5, ±0.2;** **small***** 0.99/<0.001	-0.6, ±0.5; small** 0.79/0.04	**-1.1, ±0.6;** **mod***** 0.98/0.001
Mean-to-peak force ratio	**-0.3, ±0.2;** **small*^{0}** 0.44/<0.001	**-0.2, ±0.2;** **trivial^{00}** 0.14/0.01	-0.3, ±0.2; small*^{0} 0.49/0.003	-0.4, ±0.4; small*^{0} 0.65/0.09
Peak force angle	**0.1, ±0.2;** **trivial^{00}** 0.002/0.12	**-0.1, ±0.2;** **trivial^{000}** 0.02/0.004	-0.3, ±0.4; small*^{0} 0.43/0.03	**-0.4, ±0.3;** **small*^{0}** 0.67/0.001
Oar angle variables				
Catch slip	0.1, ±0.3; trivial^{00} 0.02/0.14	0.2, ±0.3; trivial^{00} 0.006/0.24	**-0.2, ±0.2;** **trivial^{00}** 0.24/0.001	-0.2, ±0.2; trivial^{00} 0.24/0.005

Finish slip	-0.1, ±0.2; trivial^{00} 0.06/0.01	**0.1, ±0.2; trivial^{00}** 0.004/0.06	0.0, ±0.5; trivial 0.10/0.13	-0.3, ±0.3; small*^{0} 0.54/0.006
Finish angle	**-0.4, ±0.2; small**** 0.84/<0.001	-0.2, ±0.3; trivial^{0}* 0.34/0.01	-0.3, ±0.6; small 0.46/0.05	-0.1, ±1.0; trivial 0.38/0.20
Arc angle	-0.3, ±0.4; small*^{0} 0.50/0.009	0.0, ±0.3; trivial^{00} 0.03/0.07	0.0, ±0.5; trivial 0.11/0.13	0.2, ±1.0; trivial 0.18/0.40
Catch angle	0.0, ±0.5; trivial 0.14/0.15	-0.3, ±0.4; small*^{0} 0.50/0.007	-0.6, ±0.2; small 0.72/0.11	-0.2, ±0.5; trivial 0.33/0.06

M1x, men's single scull; W1x, women's single scull; M2-, men's coxless pairs; W2- women's coxless pairs.
Number of crews: 10, 8, 3 and 6 respectively.
Number of races: 17, 13, 5, 12 respectively.
Scale of magnitudes: <0.3%, trivial; 0.3-0.9%, small; 0.9-1.6%, moderate (mod); 1.6-2.5%, large; 2.5-4.1%, very large (v.large); >4.1%, extremely large (e.large).
Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely, ****most likely.
*** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005 respectively).
Reference-Bayesian likelihoods of trivial change: ^{0}possibly; ^{00}likely; ^{000}very likely, ^{0000}most likely.
Likelihoods are not shown for effects that are unclear at the 90% level (failure to reject any hypotheses: p>0.05).
Effects in **bold** have adequate precision at the 99% level (p<0.005).

Supplementary Table 4. Change in boat velocity for a change in predictor variables of two within-crew standard deviations with adjustment for stroke rate and power in the four boat classes. Data are mean (%), ±90% compatibility limits, with observed magnitude and p values for non-inferiority and non-superiority tests ($p_{–}$/p_{+}).

	M1x	W1x	M2-	W2-
Within-stroke velocity range	-0.4, ±0.6; small* 0.59/0.04	**-1.1, ±0.7; mod***** 0.96/0.005	-0.1, ±0.5; trivial 0.23/0.08	-0.1, ±0.6; trivial 0.28/0.14
Time from catch to minimum velocity	-0.1, ±0.8; trivial 0.35/0.17	-0.1, ±0.5; trivial 0.27/0.08	0.3, ±0.2; small* <0.001/0.36	-0.2, ±0.5; trivial* 0.36/0.04
Force variables				
Mean force	**-2.2, ±1.1; large***** 0.99/0.001	**-2.4, ±1.4; large***** 0.99/0.03	**-3.2, ±1.2; v.large***** 0.993/0.005	-2.6, ±1.9; v.large*** 0.96/0.009
Peak force	**-1.6, ±0.6; large***** 0.99/0.001	**-1.6, ±0.6; large****** 0.999/<0.001	-1.6, ±0.6; large**** 0.996/>0.001	-2.2, ±1.6; large*** 0.97/0.01
Rate of force development	**-0.3, ±0.3; small*^{0}** 0.55/0.003	**-0.3, ±0.2; small*^{0}** 0.47/<0.001	-0.3, ±0.5; small*^{0} 0.51/0.03	0.0, ±0.4; trivial 0.06/0.12
Time to peak force from the catch	-0.2, ±0.3; trivial^{0}* 0.36/0.003	**-0.3, ±0.2; small*** 0.31/<0.001	-0.1, ±0.4; trivial 0.14/0.05	**-0.6, ±0.5; small** 0.89/0.002
Mean-to-peak force ratio	-0.2, ±0.5; trivial 0.36/0.06	-0.2, ±0.4; trivial^{0}* 0.37/0.03	-0.0, ±0.9; trivial 0.25/0.19	-0.4, ±0.8; small 0.59/0.08
Peak force angle	**0.1, ±0.2; trivial^{000}** 0.001/0.98	**-0.1, ±0.2; trivial^{00}** 0.06/0.001	-0.3, ±0.5; small*^{0} 0.47/0.03	**-0.5, ±0.2; small**** 0.90/<0.001
Oar angle variables				
Catch slip	0.1, ±0.3; trivial^{00} 0.01/0.15	**0.2, ±0.3; trivial^{0}** 0.003/0.32	-0.0, ±0.3; trivial^{00} 0.08/0.04	-0.3, ±0.2; small*^{0} 0.43/0.001
Finish slip	-0.0, ±0.2; trivial^{000} 0.02/0.01	**0.3, ±0.3; small*^{0}** 0.002/0.58	0.0, ±0.3; trivial 0.05/0.07	-0.3, ±0.3; small*^{0} 0.60/0.003
Finish angle	-0.1, ±0.2; trivial^{00} 0.07/0.007	**0.4, ±0.3; small**** 0.001/0.77	-0.1, ±2.6; trivial 0.43/0.32	0.2, ±0.9; trivial 0.15/0.43
Arc angle	0.3, ±0.4; small*^{0} 0.02/0.46	**1.1, ±0.3; mod****** <0.001/>0.99	**0.6, ±0.3; small***** 0.002/0.97	1.1, ±1.1; mod** 0.03/0.90
Catch angle	-0.3, ±0.5; small*^{0}	**-1.0, ±0.3; mod******	-1.2, ±0.8; mod***	-0.9, ±0.7; mod**

	0.52/0.02	0.998/<0.001	0.96/0.02	0.93/0.008

M1x, men's single scull; W1x, women's single scull; M2-, men's coxless pairs; W2- women's coxless pairs.
Number of crews: 10, 8, 3 and 6 respectively.
Number of races: 17, 13, 5, 12 respectively.
Scale of magnitudes: <0.3%, trivial; 0.3-0.9%, small; 0.9-1.6%, moderate (mod); 1.6-2.5%, large; 2.5-4.1%, very large (v.large); >4.1%, extremely large (e.large).
Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely, ****most likely.
*** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005 respectively).
Reference-Bayesian likelihoods of trivial change: ^{0}possibly; ^{00}likely; ^{000}very likely, ^{0000}most likely.
Likelihoods are not shown for effects that are unclear at the 90% level (failure to reject any hypotheses: p>0.05).
Effects in **bold** have adequate precision at the 99% level (p<0.005).

Supplementary Table 5. Differences between crews in the effects of the technical variables shown in Supplementary Table 2 without adjustment in the four boat classes. Data are SD (%), ±90% compatibility limits (approximate), with observed magnitude and p values for non-inferiority and non-superiority tests ($p_{–}$/p_{+}).

	M1x	W1x	M2-	W2-
Time and velocity variables				
Stroke rate	3.4, ±1.5; e.large*** 0.02/0.98	1.1, ±0.8; large 0.05/0.94	1.5, ±1.8; v.large 0.16/0.83	1.3, ±1.1; v.large 0.06/0.93
Within-stroke velocity range	2.2, ±1.0; e.large*** 0.02/0.98	1.0, ±0.7; large** 0.05/0.95	2.1, ±2.6; e.large 0.17/0.83	1.0, ±0.9; large 0.07/0.92
Time from catch to minimum velocity	6.4, ±3.0; e.large*** 0.02/0.98	1.9, ±1.1; v.large*** 0.04/0.96	1.8, ±2.3; v.large 0.18/0.82	4.6, ±4.0; e.large 0.06/0.94
Distance per stroke	2.7, ±1.3; e.large*** 0.02/0.98	3.7, ±2.0; e.large*** 0.03/0.97	3.2, ±4.0; e.large 0.16/0.84	4.0, ±3.5; e.large 0.06/0.94
Force variables				
Mean force	**2.1, ±0.7; e.large****** 0.002/0.998	1.4, ±0.5; v.large*** 0.008/0.99	1.9, ±2.0; v.large 0.11/0.89	6.1, ±3.5; e.large*** 0.04/0.97
Power output	1.2, ±0.6; large*** 0.02/0.97	0.4, ±0.3; small** 0.04/0.90	0.6, ±0.8; mod 0.18/0.79	2.0, ±1.7; v.large 0.06/0.94
Peak force	**2.3, ±0.7; e.large****** 0.003/0.997	2.1, ±0.8; e.large*** 0.007/0.99	3.0, ±3.1; e.large 0.10/0.90	7.1, ±4.9; e.large*** 0.05/0.96
Rate of force development	**1.9, ±0.6; large****** 0.002/0.997	1.6, ±0.6; large*** 0.008/0.99	3.1, ±3.0; e.large 0.08/0.92	2.3, ±0.9; e.large*** 0.03/0.97
Time to peak force from the catch	**2.0, ±0.7; v.large***** 0.005/0.996	2.8, ±1.2; e.large*** 0.02/0.98	2.3, ±2.8; e.large 0.15/0.85	3.9, ±1.7; e.large*** 0.01/0.99
Mean-to-peak force ratio	**1.9, ±0.6; v.large****** 0.002/0.997	2.1, ±0.8; e.large*** 0.006/0.99	2.2, ±2.2; e.large 0.10/0.90	4.1, ±1.8; e.large*** 0.02/0.99
Peak force angle	**2.5, ±0.8; e.large****** 0.003/0.997	3.2, ±1.2; e.large*** 0.01/0.99	1.3, ±1.6; v.large 0.16/0.83	3.7, ±1.9; e.large*** 0.03/0.97
Oar angle variables				
Catch slip	**2.0, ±0.7; v.large****** 0.004/0.996	3.0, ±1.3; e.large*** 0.02/0.99	1.3, ±1.3; v.large 0.10/0.90	14.6, ±14.1; e.large 0.07/0.93
Finish slip	**1.6, ±0.5;**	2.5, ±1.2;	2.6, ±3.1;	5.5, ±2.6;

	v.large** 0.003/0.997	e.large*** 0.02/0.98	e.large 0.14/0.86	e.large*** 0.02/0.98
Finish angle	**2.3, ±0.8; e.large**** **0.004/0.996	3.1, ±1.3; e.large*** 0.01/0.99	13.7, ±17.4; e.large 0.15/0.85	9.9, ±7.0; e.large*** 0.05/0.96
Arc angle	**2.8, ±0.9; e.large**** **0.003/0.997	2.5, ±1.0; e.large*** 0.008/0.99	2.7, ±2.9; e.large 0.11/0.89	14.3, ±13.7; e.large 0.07/0.93
Catch angle	**3.1, ±1.0; e.large**** **0.003/0.997	2.0, ±0.8; v.large*** 0.008/0.99	2.8, ±3.1; e.large 0.12/0.88	10.6, ±10.0; e.large 0.07/0.93

M1x, men's single scull; W1x, women's single scull; M2-, men's coxless pairs; W2- women's coxless pairs.
Number of crews: 10, 8, 3 and 6 respectively.
Number of races: 17, 13, 5, 12 respectively.
Scale of magnitudes: <0.15%, trivial; 0.15-0.45%, small; 0.45-0.8%, moderate (mod); 0.8-1.26%, large; 1.26-2.02%, very large (v.large); >2.02%, extremely large (e.large).
Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely, ****most likely.
*** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005 respectively).
Likelihoods are not shown for effects that are unclear at the 90% level (failure to reject any hypotheses: p>0.05).
Effects in **bold** have adequate precision at the 99% level (p<0.005).

Supplementary Table 6. Differences between crews in the effects of the technical variables shown in Supplementary Table 3, with adjustment for power in the four boat classes. Data are SD (%), ±90% compatibility limits (approximate), with observed magnitude and p values for non-inferiority and non-superiority tests ($p_{–}/p_{+}$).

	M1x	W1x	M2-	W2-
Time and velocity variables				
Stroke rate	2.2, ±1.1; large*** 0.03/0.97	1.1, ±0.8; mod** 0.05/0.95	—[a]	1.0, ±1.0; mod 0.08/0.91
Within-stroke velocity range	0.5, ±0.7; mod 0.17/0.79	0.8, ±0.7; large 0.07/0.91	0.4, ±0.8; small 0.31/0.65	0.7, ±0.9; mod 0.14/0.84
Time from catch to minimum velocity	1.2, ±1.1; large 0.03/0.97	0.5, ±0.5; mod 0.10/0.85	0.2, ±0.5; small 0.29/0.58	0.2, ±0.4; small 0.04/0.90
Distance per stroke	1.8, ±0.8; v.large*** 0.03/0.97	1.7, ±0.9; v.large*** 0.05/0.94	0.7, ±1.3; mod 0.11/0.88	1.3, ±1.1; v.large 0.06/0.94
Force variables				
Mean force	2.4, ±0.8; e.large*** 0.005/0.99	1.4, ±1.4; v.large 0.08/0.91	0.5, ±0.6; mod 0.15/0.81	3.6, ±1.7; e.large*** 0.02/0.98
Peak force	1.6, ±0.6; v.large*** 0.01/0.99	0.9, ±0.5; large*** 0.03/0.96	1.3, ±1.6; v.large 0.18/0.82	2.4, ±1.1; e.large*** 0.02/0.98
Rate of force development	0.9, ±0.3; large*** 0.004/0.99	0.5, ±0.3; mod 0.03/0.94	0.5, ±0.6; mod 0.16/0.80	0.8, ±0.4; large*** 0.02/0.97
Time to peak force from the catch	0.6, ±0.3; mod*** 0.02/0.97	0.3, ±0.3; small** 0.03/0.86	0.5, ±0.6; mod 0.11/0.85	1.1, ±0.5; large*** 0.02/0.97
Mean-to-peak force ratio	0.6, ±0.2; mod*** 0.009/0.98	0.4, ±0.2; small*** 0.02/0.96	0.2, ±0.3; small 0.09/0.67	0.8, ±0.4; large*** 0.03/0.97
Peak force angle	0.5, ±0.2; mod*** 0.07/0.98	0.4, ±0.2; small** 0.03/0.92	0.3, ±0.4; small 0.15/0.75	0.4, ±0.4; small 0.07/0.87
Oar angle variables				
Catch slip	0.7, ±0.3; mod*** 0.007/0.99	0.5, ±0.2; mod*** 0.02/0.97	0.4, ±0.5; small 0.14/0.79	0.1, ±0.3; trivial 0.22/0.39

Finish slip	0.6, ±0.3; mod*** 0.01/0.97	0.3, ±0.3; small 0.09/0.78	0.4, ±0.5; small 0.17/0.76	—[a]
Finish angle	0.5, ±0.2; mod** 0.02/0.95	0.7, ±0.3; mod*** 0.02/0.98	0.7, ±0.5; mod** 0.05/0.94	1.4, ±1.6; v.large 0.13/0.87
Arc angle	0.9, ±0.4; large*** 0.007/0.99	0.6, ±0.3; mod*** 0.02/0.97	0.4, ±0.75; small 0.19/0.74	1.4, ±1.6; v.large 0.13/0.86
Catch angle	1.2, ±0.4; large*** 0.008/0.99	0.8, ±0.4; large*** 0.02/0.97	0.6, ±1.2; mod 0.31/0.67	0.9, ±0.5; large** 0.04/0.95

M1x, men's single scull; W1x, women's single scull; M2-, men's coxless pairs; W2- women's coxless pairs.
Number of crews: 10, 8, 3 and 6 respectively.
Number of races: 17, 13, 5, 12 respectively.
[a]Indicates insufficient data for model to converge adequately.
Scale of magnitudes: <0.15%, trivial; 0.15-0.45%, small; 0.45-0.8%, moderate (mod); 0.8-1.26%, large; 1.26-2.02%, very large (v.large); >2.02%, extremely large (e.large).
Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely, ****most likely.
*** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005 respectively).
Likelihoods are not shown for effects that are unclear at the 90% level (failure to reject any hypotheses: p>0.05).
Effects in **bold** have adequate precision at the 99% level (p<0.005).

Supplementary Table 7. Differences between crews in the effects of the technical variables shown in Supplementary Table 4 with adjustment for stroke rate and power in the four boat classes. Data are SD (%), ±90% compatibility limits (approximate), with observed magnitude and p values for non-inferiority and non-superiority tests (p_{-}/p_{+}).

	M1x	W1x	M2-	W2-
Within-stroke velocity range	0.9, ±0.8; large 0.05/0.94	1.0, ±0.9; large 0.06/0.93	0.1, ±0.5; trivial 0.40/0.48-1	0.7, ±0.8; mod 0.10/0.88
Time from catch to minimum velocity	1.2, ±1.1; large 0.08/0.91	0.7, ±0.6; mod 0.07/0.90	0.2, ±0.4; small 0.30/0.54	0.5, ±0.5; mod 0.08/0.88
Force variables				
Mean force	1.9, ±0.7; v.large*** 0.009/0.99	1.9, ±0.9; v.large*** 0.03/0.97	0.5, ±0.9; mod 0.32/0.62	2.3, ±1.4; e.large*** 0.04/0.96
Peak force	1.5, ±0.6; v.large*** 0.01/0.99	0.8, ±0.6; large** 0.04/0.93	1.0, ± 1.3; large 0.18/0.80	2.1, ±1.0; v.large 0.02/0.98
Rate of force development	0.8, ±0.4; large*** 0.006/0.99	0.4, ±0.2; small** 0.02/0.92	0.4, ±0.5; small 0.17/0.76	0.6, ±0.5; mod** 0.04/0.94
Time to peak force from the catch	0.9, ±0.4; large*** 0.02/0.98	0.3, ±0.3; small 0.05/0.87	0.5, ±0.6; mod 0.17/0.79	1.1, ±0.6; large*** 0.03/0.96
Mean-to-peak force ratio	0.6, ±0.2; mod*** 0.007/0.99	0.4, ±0.2; small*** 0.01/0.96	0.3, ±0.5; small 0.18/0.72	0.7, ±0.4; large*** 0.03/0.95
Peak force angle	0.4, ±0.2; small*** 0.01/0.96	0.3, ±0.3; small** 0.04/0.87	0.5, ±0.5; mod 0.10/0.85	0.3, ±0.3; small 0.07/0.83
Oar angle variables				
Catch slip	0.7, ±0.2; mod*** 0.006/0.99	0.5, ±0.2; mod*** 0.02/0.97	0.3, ±0.4; small 0.13/0.72	0.3, ±0.3; small 0.10/0.76
Finish slip	0.5, ±0.2; mod*** 0.01/0.97	0.5, ±0.5; mod 0.06/0.91	0.2, ±0.4; small 0.17/0.67	0.5, ±0.4; mod 0.06/0.89
Finish angle	0.5, ±0.3; mod** 0.03/0.94	0.7, ±0.3; mod 0.02/0.97	1.8, ±2.4; large 0.21/0.79	1.4 ±1.4; v.large 0.08/0.91
Arc angle	1.1, ±0.4;	0.5, ±0.3;	0.2, ±0.3;	1.5, ±1.8;

	large*** 0.005/0.99	mod*** 0.02/0.96	small 0.13/0.63	v.large 0.13/0.86
Catch angle	1.1, ±0.4; large*** 0.007/0.99	0.6, ±0.3; mod*** 0.02/0.96	0.6, ±0.9; mod 0.24/0.74	1.1, ±1.0; large 0.07/0.93

M1x, men's single scull; W1x, women's single scull; M2-, men's coxless pairs; W2- women's coxless pairs.
Number of crews: 10, 8, 3 and 6 respectively.
Number of races: 17, 13, 5, 12 respectively.
Scale of magnitudes: <0.15%, trivial; 0.15-0.45%, small; 0.45-0.8%, moderate (mod); 0.8-1.26%, large; 1.26-2.02%, very large (v.large); >2.02%, extremely large (e.large).
Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely, ****most likely.
*** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005 respectively).
Likelihoods are not shown for effects that are unclear at the 90% level (failure to reject any hypotheses: p>0.05).
Effects in **bold** have adequate precision at the 99% level (p<0.005).

Supplementary Table 8. Change in boat velocity for a change in predictor variables of two within-crew standard deviations without adjustment in the four boat classes. Data are mean (%), ±90% compatibility limits, with observed magnitude and p values for non-inferiority and non-superiority tests ($p_{–}/p_{+}$).

	Single sculls		Coxless pairs	
	Men (M1x)	Women (W1x)	Men (M2-)	Women (W2-)
Acceleration magnitude				
Maximum negative drive	**-2.3, ±0.7; large****** >0.999/<0.001	**-2.4, ±0.7; large****** 0.999/<0.001	**-2.1, ±0.6; large****** >0.999/<0.001	**-2.2, ±0.8; large****** 0.997/0.001
First peak	0.4, ±0.4; small*^{0} 0.006/0.61	0.1, ±0.5; trivial 0.08/0.31	**0.6, ±0.5; small**** 0.004/0.84	**1.1, ±0.5; mod***** 0.001/0.99
First dip	**-0.3, ±0.3; trivial**^{0}* 0.48/0.002	**-0.3, ±0.3; small***^{0} 0.53/0.001	**-0.1, ±0.1; trivial**^{0000} 0.004/<0.001	-0.0, ±0.3; trivial^{00} 0.06/0.04
Peak drive	**0.8, ±0.6; small**** 0.004/0.91	1.2, ±0.9; mod** 0.01/0.94	**1.5, ±0.3; mod****** <0.001/>0.999	1.6, ±1.4; large** 0.02/0.94
Finish dip	-0.0, ±0.4; trivial 0.14/0.11	**-0.2, ±0.2; trivial**^{0}* 0.28/0.001	0.1, ±0.5; trivial 0.08/0.22	0.4, ±0.3; small*^{0} 0.001/0.64
Peak recovery	**0.9, ±0.5; small***** 0.001/0.97	1.0, ±0.8; mod** 0.01/0.92	0.5, ±0.5; small** 0.006/0.83	0.9, ±0.8; mod** 0.01/0.90
Jerk				
Early drive phase	**1.4, ±0.5; mod****** <0.001/0.999	**1.5, ±0.5; mod****** <0.001/0.999	**1.1, ±0.5; mod***** 0.001/0.99	**1.7, ±0.8; large***** 0.001/0.99
Early-to-mid-drive phase	**-0.5, ±0.3; small**** 0.83/0.001	-0.4, ±0.4; small*^{0} 0.60/0.01	**-0.4, ±0.3; small**** 0.81/<0.001	**-0.7, ±0.4; small***** 0.96/0.002
Mid-drive phase	**1.8, ±1.1; large***** 0.01/0.99	**2.5, ±1.4; large***** 0.004/0.99	**0.9, ±0.5; mod***** 0.002/0.98	3.6, ±4.4; v.large 0.03/0.91
Late drive phase	-1.0, ±1.0; mod** 0.89/0.02	-0.8, ±0.8; small** 0.86/0.02	**-1.3, ±0.5; mod***** 0.99/<0.001	-0.2, ±0.4; trivial^{0}* 0.32/0.03
Early recovery phase	**1.0, ±0.7; mod**** 0.004/0.95	**1.4, ±0.9; mod***** 0.004/0.98	0.7, ±0.7; small** 0.02/0.84	1.2, ±1.3; mod** 0.03/0.89

Late recovery phase	**-1.9, ±0.7; large****** 0.999/<0.001	**-2.3, ±1.0; large****** 0.996/0.001	**-1.4, ±0.4; mod****** 0.999/0.001	**-2.0, ±0.7; large****** 0.997/0.001

M1x, men's singles; W1x, women's singles; M2-, men's coxless pairs; W2- women's coxless pairs.
Number of crews: 14, 9, 9 and 7 respectively.
Number of races: 25, 18, 18, 13 respectively.
Scale of magnitudes: <0.3%, trivial; 0.3-0.9%, small; 0.9-1.6%, moderate (mod); 1.6-2.5%, large; 2.5-4.1%, very large (v.large); >4.1%, extremely large (e.large).
Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely, ****most likely.
*** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005 respectively).
Reference-Bayesian likelihoods of trivial change: ^{0}possibly; ^{00}likely; ^{000}very likely, ^{0000}most likely.
Likelihoods are not shown for effects with inadequate precision at the 90% level (failure to reject any hypotheses: p>0.05).
Effects in **bold** have adequate precision at the 99% level (p<0.005).

Supplementary Table 9. Change in boat velocity for a change in predictor variables of two within-crew standard deviations with adjustment for stroke rate in the four boat classes. Data are mean (%), ±90% compatibility limits, with observed magnitude and p values for non-inferiority and non-superiority tests (p_{-}/p_{+}).

	Single sculls		Coxless pairs	
	Men (M1x)	Women (W1x)	Men (M2-)	Women (W2-)
Acceleration magnitude				
Maximum negative drive	**-3.4, ±0.5; v.large****** >0.999/<0.001	**-3.6, ±1.1; v.large****** >0.999/<0.001	**-3.7, ±1.4; v.large****** 0.999/<0.001	**-3.1, ±1.1; v.large****** 0.999/<0.001
First peak	0.2, ±0.7; trivial 0.10/0.39	1.2, ±1.1; mod** 0.02/0.92	0.9, ±1.0; small** 0.03/0.96	2.0, ±1.5; large*** 0.01/0.96
First dip	0.2, ±0.6; trivial 0.06/0.43	-0.6, ±0.5; small** 0.88/0.003	-0.1, ±0.4; trivial 0.22/0.06	-0.0, ±0.6; trivial 0.22/0.18
Peak drive	**1.8, ±0.8; large****** <0.001/0.999	**2.6, ±0.7; v.large****** <0.001/>0.999	**3.3, ±1.0; v.large****** <0.001/>0.999	**3.4, ±1.9; v.large***** 0.004/0.99
Finish dip	**-0.6, ±0.5; small**** 0.83/0.004	-0.2, ±0.7; trivial 0.36/0.12	0.4, ±0.6; small*^{0} 0.04/0.59	0.7, ±0.6; small** 0.01/0.84
Peak recovery	-0.2, ±0.7; trivial 0.37/0.13	0.5, ±1.1; small 0.12/0.60	0.2, ±1.3; trivial 0.23/0.46	-0.5, ±1.6; small 0.59/0.18
Jerk				
Early drive phase	**1.7, ±0.6; large****** <0.001/>0.999	**2.5, ±1.0; v.large****** <0.01/0.999	1.6, ±1.2; mod*** 0.01/0.96	**2.3, ±1.2; large***** 0.002/0.99
Early-to-mid-drive phase	-0.2, ±0.7; trivial 0.35/0.12	**-1.3, ±0.7; mod***** 0.98/0.002	-0.6, ±0.7; small** 0.78/0.02	**-1.2, ±0.8; mod***** 0.97/0.005
Mid-drive phase	1.8, ±1.4; large*** 0.009/0.96	**3.1, ±1.2; v.large****** <0.001/0.995	**1.5, ±0.7; mod***** <0.001/0.999	4.9, ±5.7; e.large 0.06/0.92
Late drive phase	**-1.8, ±1.0; large***** 0.99/0.002	**-1.3, ±0.8; mod***** 0.98/0.003	**-2.5, ±0.9; v.large****** 0.999/<0.001	**-1.2, ±0.7; mod***** 0.98/0.002
Early recovery phase	0.4, ±0.8; small 0.06/0.059	0.8, ±1.1; small** 0.05/0.79	0.5, ±0.9; small 0.07/0.67	-0.3, ±1.5; small 0.50/0.23

Late recovery phase	-1.4, ±1.0; mod*** 0.95/0.008	-2.6, ±1.9; v.large*** 0.97/0.01	-1.7, ±1.8; large** 0.91/0.04	-0.7, ±1.2; small 0.75/0.07

M1x, men's singles; W1x, women's singles; M2-, men's coxless pairs; W2- women's coxless pairs.
Number of crews: 14, 9, 9 and 7 respectively.
Number of races: 25, 18, 18, 13 respectively.
Scale of magnitudes: <0.3%, trivial; 0.3-0.9%, small; 0.9-1.6%, moderate (mod); 1.6-2.5%, large; 2.5-4.1%, very large (v.large); >4.1%, extremely large (e.large).
Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely, ****most likely.
*** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005 respectively).
Reference-Bayesian likelihoods of trivial change: ^{0}possibly; ^{00}likely; ^{000}very likely, ^{0000}most likely.
Likelihoods are not shown for effects with inadequate precision at the 90% level (failure to reject any hypotheses: p>0.05).
Effects in **bold** have adequate precision at the 99% level (p<0.005).

Supplementary Table 10. Change in boat velocity for a change in predictor variables of two within-crew standard deviations with adjustment for stroke rate and power in the four boat classes. Data are SD (%), ±90% compatibility limits, with observed magnitude and p values for non-inferiority and non-superiority tests ($p_{–}/p_{+}$).

	Single sculls		Coxless pairs	
	Men (M1x)	Women (W1x)	Men (M2-)	Women (W2-)
Acceleration magnitude				
Maximum negative drive	**-1.4, ±0.8; mod***** 0.98/0.001	**-1.8, ±0.7; large****** 0.997/<0.001	**-1.6, ±0.5; mod****** 0.999/0.001	**-1.0, ±0.7; mod***** 0.96/0.005
First peak	-0.1, ±0.4; trivial 0.19/0.06	-0.2, ±0.5; trivial^{0}* 0.38/0.04	0.1, ±0.5; trivial 0.66/0.26	0.4, ±0.4; small*^{0} 0.008/0.70
First dip	**-0.3, ±0.3; small*^{0}** 0.52/0.002	**-0.4, ±0.2; small**** 0.76/<0.001	**-0.2, ±0.1; trivial^{000}** 0.02/<0.001	-0.1, ±0.3; trivial^{00} 0.16/0.02
Peak drive	0.6, ±0.5; small** 0.006/0.83	0.9, ±0.9; mod** 0.02/0.90	**1.7, ±0.4; large****** <0.001/>0.999	1.2, ±1.4; mod** 0.04/0.85
Finish dip	-0.2, ±0.4; trivial^{0}* 0.34/0.03	-0.2, ±0.3; trivial^{0}* 0.31/0.004	0.1, ±0.4; trivial 0.08/0.19	0.2, ±0.4; trivial^{0}* 0.02/0.37
Peak recovery	-0.2, ±0.5; trivial 0.31/0.07	-0.1, ±0.7; trivial 0.29/0.16	-0.3, ±0.5; small*^{0} 0.51/0.03	-0.5, ±0.7; small* 0.75/0.03
Jerk				
Early drive phase	0.6, ±0.5; small** 0.009/0.82	**0.9, ±0.4; mod***** <0.001/0.99	0.3, ±0.5; small* 0.03/0.53	0.8, ±0.6; small** 0.007/0.91
Early-to-mid-drive phase	-0.2, ±0.3; trivial^{0}* 0.65/0.009	-0.2, ±0.3; trivial^{0}* 0.38/0.001	-0.2, ±0.3; trivial^{0}* 0.28/0.01	-0.4, ±0.2; small*^{0} 0.66/0.001
Mid-drive phase	1.4, ±1.0; mod*** 0.008/0.96	1.9, ±1.3; large*** 0.007/0.98	**0.8, ±0.5; small**** 0.003/0.94	2.8, ±3.6; v.large 0.07/0.89
Late drive phase	-0.8, ±0.8; small** 0.86/0.02	-0.6, ±0.6; small** 0.83/0.01	**-1.3, ±0.5; mod****** 0.997/<0.001	-0.2, ±0.4; trivial^{0}* 0.30/0.03
Early recovery phase	0.0, ±0.8; trivial 0.23/0.28	0.5, ±0.7; small*^{0} 0.03/0.69	0.1, ±0.7; trivial 0.16/0.34	-0.3, ±0.7; small 0.53/0.08

Late recovery phase	-0.7, ±0.7; small* 0.82/0.02	**-1.4, ±0.9; mod***** 0.97/0.004	**-0.8, ±0.4; small***** 0.96/<0.001	-0.5, ±0.7; small* 0.72/0.03

M1x, men's singles; W1x, women's singles; M2-, men's coxless pairs; W2- women's coxless pairs.
Number of crews: 14, 9, 9 and 7 respectively.
Number of races: 25, 18, 18, 13 respectively.
Scale of magnitudes: <0.3%, trivial; 0.3-0.9%, small; 0.9-1.6%, moderate (mod); 1.6-2.5%, large; 2.5-4.1%, very large (v.large); >4.1%, extremely large (e.large).
Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely, ****most likely.
*** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005 respectively).
Reference-Bayesian likelihoods of trivial change: ^{0}possibly; ^{00}likely; ^{000}very likely, ^{0000}most likely.
Likelihoods are not shown for effects with inadequate precision at the 90% level (failure to reject any hypotheses: p>0.05).
Effects in **bold** have adequate precision at the 99% level (p<0.005).

Supplementary Table 11. Differences between crews in the effects of the predictor variables before adjustment (in Supplementary Table 8) in the four boat classes. Data are SD (%), ±90% compatibility limits (approximate), with observed magnitude and p values for non-inferiority and non-superiority tests ($p_{–}/p_{+}$).

	Single sculls		Coxless pairs	
	Men (M1x)	Women (W1x)	Men (M2-)	Women (W2-)
Acceleration magnitude				
Maximum negative drive	1.4, ±0.6; v.large*** 0.01/0.99	1.1, ±0.7; large*** 0.04/0.95	0.8, ±0.7; large 0.06/0.93	1.1, ±1.0; large 0.07/0.92
First peak	0.7, ±0.3; mod*** 0.02/0.98	0.8, ±0.5; mod** 0.04/0.94	0.6, ±0.5; mod** 0.05/0.93	0.5, ±0.6; mod 0.11/0.85
First dip	0.5, ±0.3; mod*** 0.02/0.95	0.3, ±0.3; small 0.06/0.84	—[a]	0.3, ±0.3; small 0.06/0.84
Peak drive	1.1, ±0.5; large*** 0.01/0.98	1.5, ±0.8; v.large*** 0.03/0.97	0.4, ±0.4; small 0.10/0.81	1.9, ±1.5; v.large 0.05/0.95
Finish dip	0.9, ±0.4; large*** 0.02/0.98	0.2, ±0.3; small 0.07/0.71	0.7, ±0.4; mod** 0.04/0.95	0.3, ±0.3; small 0.06/0.82
Peak recovery	0.9, ±0.4; large*** 0.02/0.97	1.3, ±0.7; v.large*** 0.06/0.94	0.6, ±0.6; mod 0.07/0.90	1.1, ±0.9; large 0.06/0.94
Jerk				
Early drive phase	0.9, ±0.4; large*** 0.01/0.98	0.7, ±0.4; mod** 0.04/0.94	0.7, ±0.6; mod 0.07/0.92	0.9, ±0.9; large 0.07/0.92
Early-to-mid-drive phase	0.6, ±0.3; mod*** 0.02/0.96	0.6, ±0.4; mod** 0.04/0.94	0.3, ±0.3; small 0.07/0.82	0.4, ±0.5; small 0.10/0.84
Mid-drive phase	2.2, ±0.9; e.large*** 0.01/0.99	2.1, ±1.3; e.large*** 0.05/0.96	0.6, ±0.6; mod 0.07/0.91	5.6, ±4.5; e.large 0.05/0.95
Late drive phase	2.0, ±0.9; v.large*** 0.02/0.98	1.2, ±0.6; large*** 0.03/0.89	0.8, ±0.5; mod** 0.04/0.95	0.5, ±0.5; mod 0.07/0.89
Early recovery phase	1.4, ±0.6; v.large*** 0.01/0.99	1.3, ±0.8; v.large*** 0.04/0.96	1.0, ±0.6; large** 0.04/0.95	1.6, ±1.4; v.large 0.06/0.94

Late recovery phase	1.4, ±0.6; v.large*** 0.01/0.99	1.6, ±0.9; v.large*** 0.03/0.96	0.6, ±0.6; mod 0.08/0.89	1.0, ±0.8; large 0.06/0.93

M1x, men's singles; W1x, women's singles; M2-, men's coxless pairs; W2- women's coxless pairs.
Number of crews: 14, 9, 9 and 7 respectively.
Number of races: 25, 18, 18, 13 respectively.
[a]Indicates negative estimate probably due to sampling variation, so estimated as 0 and therefore no CL; true value likely similar to other boat classes.
Scale of magnitudes: <0.15%, trivial; 0.15-0.45%, small; 0.45-0.8%, moderate (mod); 0.8-1.26%, large; 1.26-2.02%, very large (v.large); >2.02%, extremely large (e.large).
Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely, ****most likely.
*** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005 respectively).
Likelihoods are not shown for effects with inadequate precision at the 90% level (failure to reject any hypotheses: p>0.05).
Effects in **bold** have adequate precision at the 99% level (p<0.005).

Supplementary Table 12. Differences between crews in the effects of the predictor variables with adjustment for stroke rate (in Supplementary Table 9) in the four boat classes. Data are SD (%), ±90% compatibility limits (approximate), with observed magnitude and p values for non-inferiority and non-superiority tests (p_{-}/p_{+}).

	Single sculls		Coxless pairs	
	Men (M1x)	Women (W1x)	Men (M2-)	Women (W2-)
Acceleration magnitude				
Maximum negative drive	1.0, ±0.5; large*** 0.02/0.98	1.8, ±0.9; v.large*** 0.03/0.97	2.2, ±1.1; e.large*** 0.03/0.97	1.4, ±1.2; v.large 0.06/0.93
First peak	1.3, ±0.5; v.large*** 0.008/0.99	1.7, ±0.8; v.large*** 0.03/0.97	1.6, ±0.8; v.large*** 0.03/0.97	2.0, ±1.4; v.large** 0.05/0.95
First dip	1.2, ±0.4; large*** 0.009/0.99	0.7, ±0.4; mod*** 0.06/0.93	0.7, ±0.4; mod** 0.04/0.95	0.8, ±0.7; large 0.06/0.93
Peak drive	1.6, ±0.6; v.large*** 0.007/0.99	1.0, ±0.5; large*** 0.05/0.95	1.5, ±0.7; v.large*** 0.03/0.96	2.4, ±1.6; e.large*** 0.05/0.95
Finish dip	1.0, ±0.4; large*** 0.08/0.99	1.0, ±0.6; large*** 0.03/0.96	1.0, ±0.5; large*** 0.03/0.96	0.8, ±0.7; large 0.05/0.94
Peak recovery	1.4, ±0.6; v.large*** 0.01/0.99	1.7, ±0.9; v.large*** 0.03/0.97	2.0, ±1.0; v.large*** 0.03/0.97	2.1, ±1.6; e.large 0.05/0.95
Jerk				
Early drive phase	1.1, ±0.5; large*** 0.01/0.98	1.5, ±0.8; v.large*** 0.03/0.94	1.8, ±1.0; v.large*** 0.03/0.97	1.4, ±1.2; v.large 0.06/0.94
Early-to-mid-drive phase	1.3, ±0.5; v.large*** 0.01/0.99	1.0, ±0.6; large*** 0.04/0.96	1.1, ±0.6; large*** 0.03/0.97	1.0, ±0.8; large 0.05/0.94
Mid-drive phase	2.8, ±1.1; e.large*** 0.008/0.99	1.9, ±1.0; v.large*** 0.03/0.97	1.0, ±0.5; large*** 0.03/0.97	7.3, ±4.9; e.large*** 0.05/0.96
Late drive phase	2.0, ±0.9; e.large*** 0.02/0.94	1.2, ±0.7; large*** 0.03/0.96	1.4, ±0.7; v.large*** 0.03/0.97	0.8, ±0.7; large*** 0.05/0.94
Early recovery phase	1.5, ±0.6; v.large***	1.7, ±0.9; v.large*** 0.01/0.99	1.7, ±0.9; v.large*** 0.03/0.97	1.9, ±1.8; v.large 0.08/0.92

Late recovery phase	2.1, ±0.9; e.large*** 0.01/0.99	3.1, ±1.5; e.large*** 0.03/0.98	2.9, ±1.5; e.large*** 0.03/0.97	1.5, ±1.4; v.large 0.07/0.92

M1x, men's singles; W1x, women's singles; M2-, men's coxless pairs; W2- women's coxless pairs.
Number of crews: 14, 9, 9 and 7 respectively.
Number of races: 25, 18, 18, 13 respectively.
Scale of magnitudes: <0.15%, trivial; 0.15-0.45%, small; 0.45-0.8%, moderate (mod); 0.8-1.26%, large; 1.26-2.02%, very large (v.large); >2.02%, extremely large (e.large).
Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely, ****most likely.
*** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005 respectively).
Likelihoods are not shown for effects with inadequate precision at the 90% level (failure to reject any hypotheses: p>0.05).
Effects in **bold** have adequate precision at the 99% level (p<0.005).

Supplementary Table 13. Differences between crews in the effects of the predictor variables with adjustment for stroke rate and power (in Supplementary Table 10) in the four boat classes. Data are SD (%), ±90% compatibility limits (approximate), with observed magnitude and p values for non-inferiority and non-superiority tests ($p_–/p_+$).

	Single sculls		Coxless pairs	
	Men (M1x)	Women (W1x)	Men (M2-)	Women (W2-)
Acceleration magnitude				
Maximum negative drive	1.6, ±0.6; v.large*** 0.01/0.99	1.1, ±0.7; large*** 0.04/0.96	0.7, ±0.6; mod 0.07/0.91	0.9, ±0.8; large 0.06/0.93
First peak	0.8, ±0.3; mod*** 0.01/0.98	0.7, ±0.5; mod** 0.04/0.94	0.7, ±0.6; mod 0.05/0.93	0.5, ±0.5; mod 0.07/0.89
First dip	0.6, ±0.3; mod*** 0.02/0.97	0.2, ±0.2; small 0.09/0.50	—[a]	0.3, ±0.3; small 0.06/0.85
Peak drive	1.0, ±0.4; large*** 0.02/0.98	1.4, ±0.7; v.large*** 0.03/0.97	0.6, ±0.5; mod** 0.05/0.92	1.9, ±1.4; v.large** 0.04/0.95
Finish dip	0.8, ±0.3; mod*** 0.02/0.98	0.4, ±0.3; small** 0.04/0.90	0.6, ±0.4; mod** 0.04/0.94	0.5, ±0.4; mod 0.05/0.91
Peak recovery	0.9, ±0.4; large*** 0.02/0.98	1.0, ±0.7; large** 0.04/0.95	0.7, ±0.6; mod 0.06/0.92	0.9, ±0.7; large 0.06/0.93
Jerk				
Early drive phase	1.1, ±0.5; large*** 0.01/0.99	0.5, ±0.5; mod 0.05/0.92	0.7, ±0.7; mod 0.07/0.92	0.7, ±0.7; mod 0.08/0.90
Early-to-mid-drive phase	0.6, ±0.3; mod*** 0.01/0.97	0.5, ±0.4; mod** 0.04/0.91	0.4, ±0.4; small 0.07/0.87	0.3, ±0.3; small 0.08/0.75
Mid-drive phase	2.0, ±0.8; e.large*** 0.01/0.99	1.9, ±1.2; v.large*** 0.04/0.96	0.7, ±0.6; mod 0.06/0.93	4.7, ±3.8; e.large 0.05/0.95
Late drive phase	1.6, ±0.8; v.large*** 0.02/0.97	1.0, ±0.5; large*** 0.04/0.96	0.7, ±0.5; mod** 0.04/0.94	0.5, ±0.5; mod 0.06/0.90
Early recovery phase	1.5, ±0.6; v.large*** 0.01/0.99	1.0, ±0.8; large 0.05/0.94	1.1, ±0.7; large*** 0.04/0.96	0.9, ±0.9; large 0.08/0.91

Late recovery phase	1.4, ±0.6; v.large*** 0.01/0.99	1.4, ±0.8; v.large*** 0.04/0.96	0.5, ±0.5; mod 0.09/0.87	0.9, ±0.8; large 0.06/0.93

M1x, men's singles; W1x, women's singles; M2-, men's coxless pairs; W2- women's coxless pairs.
Number of crews: 14, 9, 9 and 7 respectively.
Number of races: 25, 18, 18, 13 respectively.
[a]Indicates negative estimate probably due to sampling variation, so estimated as 0 and therefore no CL; true value likely similar to other boat classes.
Scale of magnitudes: <0.15%, trivial; 0.15-0.45%, small; 0.45-0.8%, moderate (mod); 0.8-1.26%, large; 1.26-2.02%, very large (v.large); >2.02%, extremely large (e.large).
Reference-Bayesian likelihoods of substantial change: *possibly; **likely; ***very likely, ****most likely.
*** and **** indicate rejection of the non-superiority or non-inferiority hypothesis (p_{N-} or p_{N+} <0.05 and <0.005 respectively).
Likelihoods are not shown for effects with inadequate precision at the 90% level (failure to reject any hypotheses: p>0.05).
Effects in **bold** have adequate precision at the 99% level (p<0.005).

Appendix B: Studies One and Two research agreement

Research Agreement

Research agreement between Victoria University and The Victorian Institute of Sport for the research undertaken by Ana Holt towards a PhD qualification.

Study Title

The validity of rowing power meters

Study Aim

Identify the level of concurrent validity and reliability of two commercially available oarlock and one oar shaft based rowing power-meters.

Study Protocol

Twenty participants will be recruited from the VIS rowing program and local rowing clubs. The participant cohort will be made up of 5 stroke-side males, 5 bow-side males, 5 stroke-side females, and 5 bow-side females. Sample size is dependent on the typical error that is being assessed, however adequate precision is expected to be achieved with a sample size of twenty participants. All potential participants will first complete a risk assessment questionnaire (appendix X) to determine whether they're medically fit to participate in the research.

Initial calibration procedures will be conducted at Victoria University in the biomechanics laboratory. This process will involve the static calibration of an instrumented ergometer –Swingulator system via the hanging of known weights (up to 40 kg) attached to the oar handle held at various positions. The student (Ana Holt) will also row a series of 30 strokes at each stroke rate between 16-35 strokes per minute, the VICON motion analysis system will be used to calibrate chain displacement of the instrumented ergometer at each stroke rate.

Formal data collection will involve participants performing a standardised 10-minute warm-up on the instrumented ergometer-Swingulator system including low intensity rowing with three 10 stroke maximal efforts. Participants will then perform a 30 second maximal effort from a stationary start. Following a subsequent 10-minute rest period participants will perform a 7 x 4 min step test on the instrumented ergometer-Swingulator system, rowing intensity and stroke rate will start low for the first three stages and progress to a maximal final stage. A 10-minute cool down period of low intensity rowing will be performed following each trial. Participants will repeat this protocol once per week over a five-week period, this will include an initial familiarisation week. All participant testing will be conducted at the VIS. Power meter devices assessed in the study will include seven Peach PowerLine, four Nielsen-Kellerman EmPower, and four WEBA OarPowerMeter devices. Devices will be allocated randomly to participant trials, with each participant performing at least two trials of each the Peach PowerLine and EmPower devices, and five trials of the OarPowerMeter (implemented concurrently with all other measures).

Concurrent validity will be assessed using the general linear mixed model procedure in SAS studio (v9.4, SAS 186 Institute Cary, NC). This statistical approach allows the partition of between and within-subject variance, to provide estimates of mean differences between devices and true device measurement error. The fixed effects in the model will be gender, participant identity, intensity, and device ID. The random effects in the model will be intensity, stroke rate, stroke count for each step-test stage and the 30 second test, mean stroke power output, and separate residuals for the three devices (to estimate device measurement error). Results will be expressed in standardised units for assessments of mean differences in means and measurement error and interpreted via non-clinical magnitude based inferences.

Uncertainty in each effect will be expressed as 90% confidence limits and as probabilities that the true effect was substantially positive or negative.

Location of Data Collection

Initial calibration of the Swingulator-ergometer system will occur in the biomechanics laboratory at Victoria Universities Footscray Park campus, where the Swingulator will be relocated for a seven-day period. Participant performance of weekly trials (warm up/down, 30 second maximal test and 7 x 4-minute step test) will occur in the gym at the Victorian Institute of Sport at Albert Park.

Equipment

The Swingulator Team Sweep Trainer used in this study is owned and will be provided in-kind from the Victorian Institute of Sport rowing program for the duration of this study. The Power meters (7 Peach PowerLine, 4 Neilsen-Kellerman EmPower, and 4 WEBA OarPowerMeter devices) are owned and will be provided in-kind from the Victorian Institute of Sport rowing program for the duration of this study. The Concept II Model D ergometer has been purchased from the student Ana Holt's PhD budget and is the property of Victoria University. The instrumentation attached to the Concept II ergometer has been developed by employees of and therefore is the property of Victoria University.

Intellectual Property Rights

The student Ana Holt will retain ownership of all intellectual property generated through the course of the research conducted as per Victoria University's 2013 intellectual property regulations.

Publication

The results of the research will be published as a PhD thesis and submitted for publication to peer-reviewed journals. Results of the research may also be published in conference abstract, book, report, internet, and presentation form.

Role	Name	Organisation	Signature	Date
Chief Investigator	Professor Robert Aughey	Victoria University	Robert Aughey	Digitally signed by Robert Aughey [illegible]
Associate Investigator	Dr. Rodney Siegel	Victoria Institute of Sport	[redacted]	23/04/18
Associate Investigator	Dr. Kevin Ball	Victoria University	[redacted]	23/04/18
Student Investigator	Ana Holt	Victoria University	[redacted]	23/04/18
VIS Rowing Head Coach	Simon Gadsden	Victoria Institute of Sport	[redacted]	24.4.17

Appendix C: Study Three and Four research agreement

Research Agreement

Research agreement between Victoria University and The Victorian Institute of Sport for the research undertaken by Ana Holt towards a PhD qualification.

Study Title

Technical Determinants of On-water Rowing Performance

Study Aim

To investigate how rowing technique influences boat speed.

Study Protocol

Thirty athletes (male and female) will be recruited from the VIS rowing program and rowing clubs. All participants will be over the age of 18.

Rowers will be required to complete a risk assessment questionnaire to ensure they're medically fit to participate in the research, and a questionnaire about their rowing history. Participants will perform a maximal 2000 m time trial where measures of rowing technique will be collected from a GPS (OptimEye S5, Catapult Australia) and a Peach Powerline power meter attached to the boat. Data will be collected from regattas where possible, with data collected from time trials at the National Aquatic Centre in Carrum otherwise. The technical variables assessed will include: power output, total arc length, effective length, catch and finish angles, position of peak acceleration, negative acceleration magnitude, and catch and finish slips and boat speed. Statistical analysis will be achieved via a general linear mixed model procedure in SAS Studio (v9.4, SAS Institute, Cary, NC).

Individual results will be provided to participants in report form and to participants' coaches only if participants have provided consent to do so on their consent forms. A report detailing the overall findings of the study will be provided to the VIS rowing program on completion of data-analysis, however individual participant data will remain confidential.

Equipment Use and Ownership

Eight sweep and four sculling Peach PowerLine power meters will be provided in-kind by the VIS rowing program, these devices will be used throughout the duration of this study (which will include being lent to non-VIS rowing scholarship rowers) for data collection purposes. The VIS will retain ownership of these power meter devices upon completion of the study. Nine OptimEye S5, Catapult GPS tracking devices will be provided in-kind by the VIS rowing program for use throughout the study. The VIS rowing program will maintain ownership of these devices throughout and on completion of the study.

Intellectual Property Rights

The student Ana Holt will retain ownership of all intellectual property generated through the course of the research conducted as per Victoria University's 2013 intellectual property regulations.

Publication

The results of the research will be published as a PhD thesis and submitted for publication to peer-reviewed journals. Results of the research may also be published in conference abstract, book, report, internet, and presentation form.

Role	Name	Organisation	Signature	Date
Chief Investigator	Professor Robert Aughey	Victoria University	[redacted]	26/03/2019
Associate Investigator	Dr. Rodney Siegel	Victoria Institute of Sport		14/01/19
Associate Investigator	Dr. Kevin Ball	Victoria University		29/01/19
Student Investigator	Ana Holt	Victoria University / Victorian Institute of Sport		14/01/19
Performance Manager	Rob Leeds	Victoria Institute of Sport		15/01/19
Sports Science Coordinator	Harry Brennan	Victoria Institute of Sport		18/01/19

Appendix D: Study Five research agreement

Research Agreement

Research agreement between Victoria University and The Victorian Institute of Sport for the research undertaken by Ana Holt towards a PhD qualification.

Study Title

Physiological Determinants of On-water Rowing Performance

Study Aim

Investigate differences in rowers' physiology and how these differences relate to racing performances over 2000 m.

Study Protocol

Thirty athletes (male and female) will be recruited from the VIS rowing program and local rowing clubs. All participants will be over the age of 18.

Participants will perform an on-water rowing step-test at consisting of 6 x 4-min submaximal stages of progressive intensity to establish power and oxygen consumption ($\dot{V}O_2$) at the first and second lactate thresholds, followed by one maximal 4-min stage to establish maximal oxygen consumption ($\dot{V}O_{2max}$) and final stage mean power output. Expired air will be collected and analysed during the on-water step test via a portable metabolic gas-analysis system (Cosmed K4b2, Italy). A one-minute rest period between stages will allow for the collection of blood lactate at the end of each stage by a 0.5 µl fingertip blood sample, and immediate analysis using a portable lactate analyser (The Edge blood lactate analyser, ApexBio, Taiwan). Heart rate (Garmin Forerunner, 920XT, Garmin, Australia), rating of perceived exertion (RPE) and power output will also be collected throughout the test. Participants will perform on-water step-tests at The National Water Sports Centre in Carrum Downs.

On-water rowing time trials over 2000 m, 5700 m, and 100 m and a 10-stroke peak power test will be performed by participants at The National Water Sports Centre in Carrum Downs to assess rowing performance. Time will be recorded from 2000 m time trials using a GPS tracking device (OptimEye S5, Catapult, Australia), power output via gate-based power meters (EmPower, Neilsen-Kellerman) and heart rate (Garmin Forerunner, 920XT, Garmin, Australia) will also be recorded throughout the time trials.

A five-zone model will be used to establish heart rate and power training zones as approximately: T1 (<70% HR_{max} [maximal heart rate], <50% $\dot{V}O_{2max}$ power [power at $\dot{V}O_{2max}$], ≤18 strokes·min^{-1}); T2 (70-80% HR_{max}, 50-60% $\dot{V}O_{2max}$ power, 18-20 strokes·min^{-1}); T3 (80-88% HR_{max}, 60-75% $\dot{V}O_{2max}$ power, 20-24 strokes·min^{-1}); T4 (88-92% HR_{max}, 75-85% $\dot{V}O_{2max}$ power, 24-28 strokes·min^{-1}); T5 (>92% HR_{max}, >85% $\dot{V}O_{2max}$ power, ≥28 strokes·min^{-1}). participant identity and interactions with fixed effects to allow for individual responses to training. Pearson's correlation coefficients will be established between physiological measures and measures of rowing performance (2000 m time and mean power output). Individual results will be provided to participants in report form and to participant's coaches only if participants have provided consent to do so on their consent forms. A report detailing the overall findings of the study will be provided to the VIS rowing program on completion of data-analysis, however individual participant data will remain confidential.

Equipment Use and Ownership

Eight sweep and four sculling Peach PowerLine power meters will be provided in-kind by the VIS rowing program, these devices will be used throughout the duration of this study (which will include being lent to non-VIS rowing scholarship rowers) for data collection purposes. The VIS will retain ownership of these power meter devices upon completion of the study. Nine OptimEye S5, Catapult GPS tracking devices will be provided in-kind by the VIS rowing program for use throughout the study. The VIS rowing program will maintain ownership of these devices throughout and on completion of the study. Four of The Edge portable blood lactate analysers will be provided in-kind by the VIS rowing program for use during on-water step testing, and will be returned on completion of each testing bout. All consumables used during step testing (The Edge lactate strips, alcohol swabs, tissues, gloves) will be purchased via Ana Holt's PhD budget and will remain in her possession throughout conduction of the research.

Three portable Cosmed K4 metabolic gas-analysis systems will be provided in-kind from Victoria University for use during On-water step testing, and will be returned to Victoria University following completion of each testing bout.

Intellectual Property Rights

The student Ana Holt will retain ownership of all intellectual property generated through the course of the research conducted as per Victoria University's 2013 intellectual property regulations.

Publication

The results of the research will be published as a PhD thesis and submitted for publication to peer-reviewed journals. Results of the research may also be published in conference abstract, book, report, internet, and presentation form.

Role	Name	Organisation	Signature	Date
Chief Investigator	Professor Robert Aughey	Victoria University	Robert Aughey	Digitally signed by Robert Aughey DN: cn=Robert Aughey, o=Victoria University, ou=Institute of Sport, Exercise and Active Living, email=robert.aughey@vu.edu.au, c=AU Date: 2019.01.14 [illegible]
Associate Investigator	Dr. Rodney Siegel	Victoria Institute of Sport	[redacted]	11/12/18
Associate Investigator	Dr. Kevin Ball	Victoria University	[redacted]	11/12/18
Performance Manager	Rob Leeds	Victoria Institute of Sport	[redacted]	17/01/19
Sport Science Coordinator	Harry Brennan	Victoria Institute of Sport	[redacted]	21/01/19
Student Investigator	Ana Holt	Victoria University	[redacted]	11/12/18

Appendix E: Study Two participant information sheet

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

INFORMATION TO PARTICIPANTS INVOLVED IN RESEARCH

You are invited to participate

You are invited to participate in a research project entitled: The validity of three rowing power meters.

This project is being conducted by a student researcher Ana Holt as part of a PhD study at Victoria University under the supervision of Professor Robert Aughey from the Institute for Health and Sport.

Project explanation

This project will be looking at three different brands of power meter devices that measure the effort applied by rowers to the oar to determine whether the information these devices provide is accurate. The effect of wind direction and speed as well as other weather factors makes it difficult to measure and compare on-water rowing performance between rowers and on different occasions such as comparing your boat speed or race time in different regattas throughout the season to see how you are improving, as a strong headwind will slow you down even if you are able to work harder than in earlier regattas. Power meters allow the measurement of the work you perform every stroke and are not affected by the weather. So, the use of power meters in rowing would allow comparisons of rowing performance on different occasions and between rowers. But before we can be sure that power meters are accurate they first need to be compared against a measure of power that we know is correct to make sure that what the power meter devices are measuring is correct. Therefore, this study aims to determine whether three different brands of power meter devices are providing correct information during rowing at different levels of effort.

What will I be asked to do?

You will be asked to attend the Victorian Institute of Sport five times: once a week for about one hour each time, over a five-week period. While at the Victorian Institute of Sport you will be asked to perform a training session on a Swingulator rowing ergometer (shown in figure 1), the training will be similar to the training you are used to performing for rowing. Further information about what you will be doing in the study can be found below in the section "How will the research be conducted?".

What will I gain from participating?

You will experience training out of the Victorian Institute of Sport, where many of Australia's best elite athletes train. The outcome of this study will give you a measure of your current rowing performance ability. You may also have the opportunity to train with a power meter device on your boat for an entire 2018-2019 rowing season in upcoming research conducted in this PhD, giving you instant feedback on your rowing technique and work done during training sessions. Please note that participation in the study is not related to the VIS scholarship program or selection process.

How will the information I give be used?

All of the information collected from you during the study will be confidential and will remain confidential after the study has finished to protect your privacy, that is your involvement in the study will not be shared with anyone and your name will not be on any information collected from your during the study. The information collected from you will be used to see if the power meter devices tested provide reliable and valid outputs, that is whether they consistently tell us correct information across a range of rowing intensities and are accurate enough to allow us to be sure that any improvements in a rower's power output are due to actual improvements in work output. This will be achieved by comparing the power you produce each stroke that you row during the testing between each of the power meter devices, a rowing ergometer equipped with technology to give us an accurate measure of your power output, and a Concept II rowing ergometer that will be tested during the study.

What are the potential risks of participating in this project?

As with your usual rowing training there is a risk of experiencing fatigue (tiredness), muscle soreness, stiffness, soft tissue injury, and performance related anxiety. There is a low risk that you may experience breathlessness, light headedness, nausea, vomiting and fainting following maximal intensity exercise (i.e. as hard as you can go), and a very low risk of vasovagal (heart related) episodes or even sudden death. However, these risks will be minimised by your completion of a risk assessment questionnaire which will check whether you're medically fit to participate in the research. Also, your recent training and competition involvement in rowing should reduce your risk of experiencing these symptoms. Testing will be stopped for your safety if you experience any of the following: you wish to stop; severe leg pain or any other severe pain related to exercise; onset of chest pain; severe shortness of breath or difficulty breathing; light headedness; or if you show unexpected signs of metabolic or cardiorespiratory distress.

How will this project be conducted?

You will be required to complete an initial risk assessment questionnaire to check that you are medically fit to participate in the research, and you will also be asked to complete a questionnaire about your rowing training history. You will then be asked to attend the Victorian Institute of Sport five times: once a week for about one hour each time, over a five-week period. During each of your visits your height and weight will be measured, you will then be asked to complete a 10-minute warm up on the Swingulator rowing ergometer (pictured in figure 1) at a low (easy/light rowing) intensity and including three 10-stroke bursts as hard as you can. You will then be asked to perform 30 seconds of maximal rowing on the Swingulator (as hard as you can), this will be followed by a 10-minute rest period where you will be able to get off the Swingulator, walk around and stretch. After the rest period, you will be asked to perform a 7 x 4-minute step test on the Swingulator, where you will row for four minutes at an intensity given to you by Ana Holt, the intensity will get harder for each of the six remaining four minute stages with a final maximal stage (as hard as you can go for four minutes). Finally, you will be asked to complete a 10-minute warm down on either the Swingulator or a Concept II rowing ergometer at a low (easy/light rowing) intensity. During each of 30 second and 7 x 4 minute tests your power output will be recorded from power meter devices on the oar shaft, at the gate where the oar is held, from technology attached to the Concept II rowing ergometer, and the Concept II rowing ergometer itself. The power meters used on the oar shaft and gate will be randomly allocated to participants, so will be different each time you attend the Victorian Institute of Sport for testing, however this will have no effect on your rowing performance.

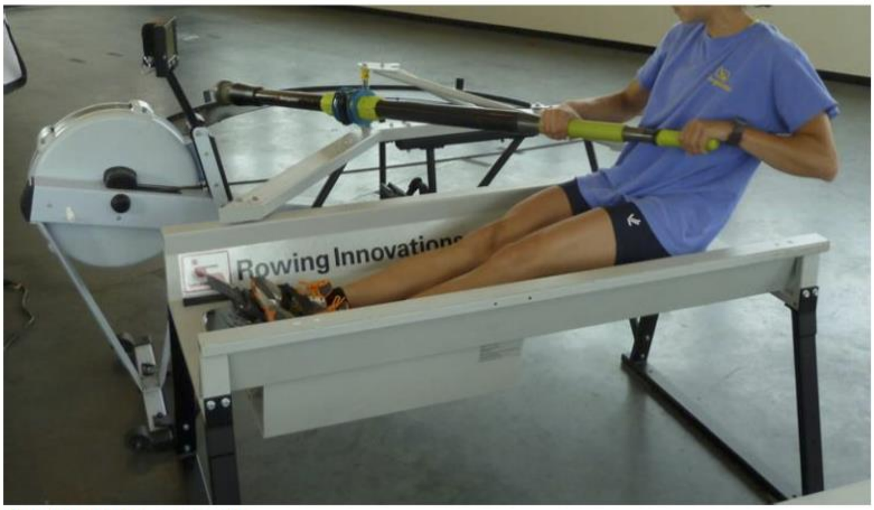

Figure 1. Swingulator rowing ergometer.

Who is conducting the study?

Victoria University
Footscray Park
Ballarat Rd,
Footscray 3011
Victoria

Victorian Institute of Sport
Lakeside Stadium,
33 Aughtie Drive,
Albert Park 3206
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Chief Investigator:
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Ph. 61 3 9919 6329
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Student Investigator:
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Co-investigator:
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Sport Science, Victorian Institute of Sport
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Co-Investigator:
Dr. Kevin Ball
Institute for Health and Sport, Victoria University
kevin.ball@vu.edu.au

Any queries about your participation in this project may be directed to the Chief Investigator listed above.
If you have any queries or complaints about the way you have been treated, you may contact the Ethics Secretary, Victoria University Human Research Ethics Committee, Office for Research, Victoria University, PO Box 14428, Melbourne, VIC, 8001, email researchethics@vu.edu.au or phone (03) 9919 4781 or 4461.

Appendix F: Study Two recruitment flyer

Appendix G: Study Two participant consent

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

CONSENT FORM FOR PARTICIPANTS INVOLVED IN RESEARCH

INFORMATION TO PARTICIPANTS:
We would like to invite you to be a part of a study looking at three different brands of power meter devices that measure the effort applied by rowers to the oar to determine whether the information these devices provide is accurate.

This study aims to establish whether the work output recorded from three different brands of rowing power meters is correct. Participation in the study will involve completing a maximal 30 second rowing test (as hard as you can go for 30 s), 7 x 4-minute step test of increasing intensity from low/light rowing to maximal (as hard as you can go for four minutes) and both a 10-minute warm up and warm down at low/light intensities, completed once a week for five weeks. Height and weight will also be recorded and participants will be required to complete risk assessment and training history questionnaires to ensure you're medically fit to participate in the study. Potential risks associated with the project include the risk of experiencing fatigue (tiredness), muscle soreness, stiffness and soft tissue injury from rowing. There is a low risk of experiencing breathlessness, light-headedness, nausea, vomiting, fainting, or performance related anxiety, and a very low risk of vasovagal (heart related) episodes or sudden death following maximal exercise.

CERTIFICATION BY PARTICIPANT

I, "[Click here & type participant's name]"
of "[Click here & type participant's suburb]"

I certify that I am at least 18 years old and that I am voluntarily giving my consent to participate in the study:
The validity of three rowing power meters being conducted at Victoria University by: Professor Robert Aughey.

I certify that the objectives of the study, together with any risks and safeguards associated with the procedures listed hereunder to be carried out in the research, have been fully explained to me by:

Ana Holt

and that I freely consent to participation involving the below mentioned procedures:

- ☐ Completion of a risk assessment questionnaire to determine if I'm medically fit to participate
- ☐ Completion of a questionnaire regarding my recent training history
- ☐ Attendance at the Victorian Institute of Sport on five occasions over a five-week period for approximately one hour each week.
- ☐ Measurement of my height and weight
- ☐ Successive performance of the following per week on a rowing Swingulator system (rowing ergometer):
    - 10-minute warm up
    - 30 second maximal rowing test
    - 7 x 4-minute step test of incremental intensity each step from low intensity to a final maximal step.
    - 10-minute warm down

I certify that I have had the opportunity to have any questions answered and that I understand that I can withdraw from this study at any time and that this withdrawal will not jeopardise me in any way.

I certify that I am in good health and am not currently suffering from any injury or illness which may impair my physical performance, health or wellbeing.

I have been informed that the information I provide will be kept confidential.

I agree to allow the use of my collected data to be used for research, including journal publications and post-graduate thesis

I agree to be contacted by the student investigator Ana Holt or Chief Investigator Professor Robert Aughey regarding my interest in participating in future research conducted for this PhD project (this will not influence your participation in the current study) **Yes/No** (please circle).

Signed:
Date:

Any queries about your participation in this project may be directed to the researcher
Professor Robert Aughey
61 3 9919 6329

If you have any queries or complaints about the way you have been treated, you may contact the Ethics Secretary, Victoria University Human Research Ethics Committee, Office for Research, Victoria University, PO Box 14428, Melbourne, VIC, 8001, email Researchethics@vu.edu.au or phone (03) 9919 4781 or 4461.

Appendix H: Study Three and Four participant information sheet

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

INFORMATION TO PARTICIPANTS INVOLVED IN RESEARCH

You are invited to participate

You are invited to participate in a study entitled: Technical Determinants of On-water Rowing Performance

This project is being conducted by a student researcher Ana Holt as part of a PhD study at Victoria University under the supervision of Professor Robert Aughey from the Institute for Health and Sport.

Project explanation

This study will examine how different aspects of rowing technique influence boat speed to determine which part of a rower's technique has the biggest influence on improving boat speed and rowing performance. The outcomes of this research will help direct the coaching of technique to maximise boat speed as well as providing individual feedback on strengths and weaknesses to participants about their rowing technique.

What will I be asked to do?

You will be asked to perform a 2000 m on-water rowing time trial performed in as fast time as possible in either a single scull or pair oared boat at a regatta you will be attending at the Sydney International Regatta Centre, Penrith, New South Wales. You will also be asked to complete a medical questionnaire prior to completing the time trial to determine if you are medically fit to participate. Further information about what you will be doing in the study can be found below in the section "How will this project be conducted?".

What will I gain from participating?

Your rowing technique will be assessed in-depth and you will be provided with an individualised report highlighting the areas of your technique that have the biggest impact on improving your boat speed, and those areas that have the biggest effect on slowing your boat down. This information will help you maximise your boat speed by showing you which areas of your technique you should focus on to get the best improvement in rowing performance. Should you choose to share this information with your coach, your coach will also be provided with detailed information regarding your technique and how it is impacting your racing performance. Please note that participation in the study is not related to the VIS scholarship program or selection process, and your decision to participate in this research will have no impact on your rowing career.

How will the information I give be used?

All of the information collected from you during the study will be confidential and will remain confidential after the study has finished to protect your privacy, that is your involvement in the study will not be shared with anyone and your name will not be on any information collected from you during the study. If you agree to share the information collected from you with your coach (through circling "yes" to this question on your consent form and providing your coaches name) then the information collected from you during the study will be shared with your coach. However, you can change your mind at any time during the study and discontinue sharing your information, or choose not to share any information with your coach (by circling "no" to this question on your consent form) and neither decision will impact your participation in the study.

The information collected from you throughout the study will be used to see how changes in rowers' technique are related to boat speed. The findings of this research will be presented at conferences and published in a thesis and sport science journals.

What are the potential risks of participating in this project?

As with your usual rowing training there is a risk of experiencing fatigue (tiredness), muscle soreness, stiffness, soft tissue injury, and performance related anxiety. There is a low risk that you may experience breathlessness, light headedness, nausea, vomiting and fainting following maximal intensity exercise (i.e. as hard as you can go), and a very low risk of vasovagal (heart-related) episodes or even sudden death. However, these risks will be minimised by your completion of a risk assessment questionnaire which will check whether you're medically fit to participate in the research. Also, your recent training and competition involvement in rowing should reduce your risk of experiencing these symptoms. You are advised to stop the time trial for your safety if you experience any of the following: you wish to stop; severe leg pain or any other severe pain related to exercise; onset of chest pain; severe shortness of breath or difficulty breathing; light headedness; or if you show unexpected signs of metabolic or cardiorespiratory distress. There is also a risk of collision or capsize and a small risk of drowning associated with on-water rowing.

How will this project be conducted?

You will be required to complete initial risk assessment questionnaire to check that you are medically fit to participate in the research. You will then be asked to perform a 2000 m on-water rowing time trial performed in as fast time as possible in either a single scull or pair oared boat. The time trial will be completed as a race performed at an upcoming regatta you will be competing in at the Sydney International Regatta Centre, Penrith, New South Wales. Prior to the time trial a power meter will be attached to the gate of your boat to record your power output (the effort you are applying on the oars) and the position of your oars throughout the time trial. A GPS device will also be attached to the stern of your boat to record your boat speed and acceleration during the time trial – neither of these devices will affect your rowing in any way. Following your completion of the time trial both devices will be removed from your boat and you will be provided with a detailed report of your technique once the data collected from you has been analysed.

Who is conducting the study?

Victoria University
Footscray Park
Ballarat Rd,
Footscray 3011
Victoria

Victorian Institute of Sport
Lakeside Stadium,
33 Aughtie Drive,
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Victoria

Chief Investigator:
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Sport Science, Victorian Institute of Sport
rodney.siegel@vis.org.au

Co-Investigator:

Appendix I: Study Three and Four participant consent form

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

CONSENT FORM FOR PARTICIPANTS INVOLVED IN RESEARCH

INFORMATION TO PARTICIPANTS:
We would like to invite you to be a part of a study looking at how rowing technique is related to boat speed.

This study aims to investigate how different aspects of rowing technique influence boat speed to determine which part of a rower's technique has the biggest influence on improving boat speed and rowing performance. Participation in this study will require you to complete risk assessment questionnaire to ensure you're medically fit to participate in the study. You will also be asked to perform a 2000 m time trial (with the aim of completing the distance in as fast time as possible) in either a single scull or pair oared boat. The time trial will be completed as a race performed at a regatta you will be attending at the Sydney International Regatta Centre, Penrith, New South Wales. You will have a GPS device attached on the stern of your boat to record boat speed and acceleration, and a power meter device attached at your gate to record power output (the effort you are applying to the oars) and oar position for each stroke performed throughout the time trial. Potential risks associated with the project include the risk of experiencing fatigue (tiredness), muscle soreness, stiffness and soft tissue injury from rowing, a low risk of experiencing breathlessness, light-headedness, nausea, vomiting, fainting, or performance related anxiety, and a very low risk of vasovagal (heart related) episodes or sudden death following maximal exercise.

CERTIFICATION BY PARTICIPANT

I ....
of ....

I certify that I am at least 18 years old and that I am voluntarily giving my consent to participate in the study: Technical Determinants of On-water Rowing Performance being conducted at Victoria University by Professor Robert Aughey.

I certify that the objectives of the study, together with any risks and safeguards associated with the procedures listed hereunder to be carried out in the research, have been fully explained to me by:

Ana Holt

and that I freely consent to participation involving the below mentioned procedures:

- Completion of a risk assessment questionnaire to determine if I'm medically fit to participate
- Performance of a maximal on-water 2000 m rowing time trial where my boat speed, acceleration, power output and oar position will be collected throughout.

I certify that I have had the opportunity to have any questions answered and that I understand that I can withdraw from this study at any time and that this withdrawal will not jeopardise me in any way.

I certify that I am in good health and am not currently suffering from any injury or illness which may impair my physical performance, health or wellbeing.

I have been informed that the information I provide will be kept confidential.

I agree to share my data collected with my coach (by agreeing your data will **only** be shared with the coach you specify below. You are entitled to withdraw your consent to share your data with your coach at any time. If you do not wish (or no longer wish) to share your data with your coach this will not influence your participation in the study in any way).

Coaches Name:______________________________ **Yes/No** (please circle)

I agree to allow my photo to be taken during my participation in the study and any photos of me taken to be shown in presentation of the research at conferences or otherwise (all photos taken will have faces blocked out and will not be identifiable. Your decision will not influence your participation in the study in any way). **Yes/No** (please circle)

I agree to be contacted by the student investigator Ana Holt or Chief Investigator Professor Robert Aughey regarding my interest in participating in future research conducted for this PhD project (this will not influence your participation in the current study) **Yes/No** (please circle).

I agree to allow the use of my collected data to be used for research, including journal publications and post-graduate thesis

Signed:
Date:

Any queries about your participation in this project may be directed to the researcher
Professor Robert Aughey
61 3 9919 6329

If you have any queries or complaints about the way you have been treated, you may contact the Ethics Secretary, Victoria University Human Research Ethics Committee, Office for Research, Victoria University, PO Box 14428, Melbourne, VIC, 8001, email Researchethics@vu.edu.au or phone (03) 9919 4781 or 4461.

Appendix J: Study Five participant information sheet

INFORMATION TO PARTICIPANTS INVOLVED IN RESEARCH

You are invited to participate

You are invited to participate in a research project titled: longitudinal monitoring of training characteristics in rowing.

This project is being conducted by a student researcher Ana Holt as part of a PhD study at Victoria University under the supervision of Professor Robert Aughey from the Institute for Health and Sport.

Project explanation

This project will be looking at how differences in training (such as how hard, long and far training sessions are) result in differences in rowing race performances. The power meters used in this study are devices that act as the gate on a boat's rigger and allow measurement of how hard the rower is pulling on the oars, giving a measure of the type of training they are doing. The findings from this research will identify which aspects of rowing training are most important for improving rowing performance.

What will I be asked to do?

You will be asked to record heart rate and power output (how hard you pull on the oars each stroke) using a provided heart rate monitor (watch and chest strap) and power-meter (put on your boat in the place of your gate) during all of your training sessions from September 2019 through to the end of the rowing season (April 2020). The training sessions you record heart rate and power from will include on-water rowing, ergometer rowing, cycling and running (only heart rate needs to be recorded from running and cycling training). You will be asked to upload your heart rate data from each training session performed throughout the domestic season to the password protected online software TrainingPeaks. You will be asked to perform four 2000 m time trials throughout the domestic rowing season, these can be in the form of racing at regattas in Victoria (Lake Wendouree, Ballarat, the National Water Sports Centre, Carrum or Lake Nagambie, Nagambie) or at the Sydney International Regatta Centre, Penrith, New South Wales. You will also be asked to complete three on-water step-tests in September, December 2019 and April 2020 (after National Champs), these will take approximately one hour each and will be held either at the National Water Sports Centre, Carrum or on Albert Park Lake, Albert Park, Victoria. The step-tests will involve rowing 7 x 4-minute stages with one-minute break between each stage. The step-test will start at a low/easy effort, and effort become progressively harder each stage until a final (seventh) maximal effort stage. Further information about what you will be doing in the study can be found below in the section "How will this project be conducted?".

What will I gain from participating?

You will be given a power meter device to put on your boat and use for the entire season. The power meter replaces the gate on your rigger and does not limit the rowing movement in any way, but will give you instant feedback on your power output (the effort of your rowing). You will find out your training zones (ranges of heart rate and power output that are individual to your physiological capacity) and maximal rate of oxygen uptake (VO_{2max}) for on-water rowing (which will be different to what they are on the ergometer). You can use this information to guide your rowing training as you will be able to use the power meter to determine which on-water power zones you are rowing in. This study does not require you to change your training at all, we will just be recording it and monitoring your performance. Please note that participation in the study is not related to the Victorian Institute of Sport scholarship program or selection process.

How will the information I give be used?

All of the information collected from you during the study will be confidential and will remain confidential after the study has finished to protect your privacy, that is your involvement in the study will not be shared with anyone and your name will not be on any information collected from your during the study. Please note that the power meter on your boat may make it obvious to others that you are participating in the study, and therefore your participation may be known by other athletes and coaches. The heart rate data you upload to the online software TrainingPeaks will be accessible by yourself (through a password protected account) and the research investigators listed at the end of this information sheet only. If you agree to share the information collected from you with your coach (through circling "yes" to this question on your consent form and providing your coaches name) then the information collected from you during the study will be shared only with the coach that you have nominated. However, you can change your mind at any time during the study and stop sharing your information, or choose not to share any information with your coach (by circling "no" to this question on your consent form, or leaving the question unanswered) and neither decision will impact your participation in the study.

The information collected from you throughout the study will be used to see how differences in training characteristics between individuals (such as how hard, far and long training sessions are) result in differences in rowing performance over a 2000 m race. The information collected from you during on-water step testing (details in the section "How will this project be conducted" below) will provide information on what effort relative to your individual physiological capacity the training you are doing is at, informing your training characteristics. The data collected throughout this study will be used in a PhD thesis , will be reported in publications and reports, and will be presented at scientific meetings and conferences.

What are the potential risks of participating in this project?

There is a risk that other rowers and coaches will know about your participation in this study, as the power meter on your boat will be obvious to others. As with your usual rowing training there is a risk of experiencing fatigue (tiredness), muscle soreness, stiffness, soft tissue injury, and performance related anxiety. There is a low risk that you may experience breathlessness, light headedness, nausea, vomiting and fainting following maximal intensity exercise (i.e. as hard as you can go), and a very low risk of vasovagal (heart-related) episodes or even sudden death. However, these risks will be minimised by your completion of a risk assessment questionnaire which will check whether you're medically fit to participate in the research. Also, your recent training and competition involvement in rowing should reduce your risk of experiencing these symptoms. On-water step tests will be stopped for your safety if you experience any of the following: you wish to stop; severe leg pain or any other severe pain related to exercise; onset of chest pain; severe shortness of breath or difficulty breathing; light headedness; or if you show unexpected signs of metabolic or cardiorespiratory (heart-related) distress. It is recommended you stop rowing if you experience any of these symptoms during training, 2000 m racing, or during any of the time trials undertaken during this study. There is also a risk of infection and bruising from blood lactate samples taken from your finger during on-water step-tests, but sterile equipment will be used and appropriate sampling procedures followed to reduce the likelihood of this occurring. There is also a risk of collision or capsize and a small risk of drowning associated with rowing on-water whilst wearing the portable metabolic system (facemask), however two coach boats will be on-water to assist you in the event of capsize and megaphones will be used to direct boats away from each other to avoid collision. Please note you will not be included in the study if you are pregnant, have any injury or medical condition that would not consider you to be medically fit to participate.

How will this project be conducted?

You will be required to complete an initial risk assessment questionnaire to check that you are medically fit to participate in the research, and you will also be asked to complete a questionnaire about your rowing training history. You will then be provided with a Garmin Forerunner heart rate monitor and Peach PowerLine power meter which you will be asked to use to record your heart rate and power output for every training session (including any competition events and non-rowing training sessions) throughout the rowing season (September 2018 to April 2019). Please note you will be shown how to use both of these devices and the power meter will be set up on your boat for you. You will also be asked to perform a 2000 m time trial (completed in the quickest time you can do) in September, December, February and April, this can take the form of racing undertaken at regattas in small boats (singles and pairs) at regattas held at Lake Wendouree, Ballarat, the National Water Sports Centre, Carrum or Lake Nagambie, Nagambie or the Sydney International Regatta Centre, Penrith, New South Wales.

You will also be asked to perform a 7 x 4-minute on-water step-test in September, December and April. This will involve rowing on-water in small boats (singles or pairs) where you will wear a portable gas analyser which is worn like a backpack and will involve breathing into a facemask. At the end of each 4-minute stage you will have a one-minute rest period where a small (pin-head size) sample of blood will be taken from your fingertip to test your blood lactate levels (as a measure of your energy production) and you will be asked to rate how hard the last 4-minute stage felt on a scale of 6-20. The first stage will start off at a low/easy intensity, with each 4-minute stage getting harder until the final stage which will be performed maximally (as hard as you can go over 4-minutes). Your power output and heart rate will also be

recorded continuously throughout the step-tests. Step-tests will be performed at either the National Water Sports Cent
Carrum or on Albert Park Lake, Albert Park.

Who is conducting the study?

Victoria University
Footscray Park
Ballarat Rd,
Footscray 3011
Victoria

Victorian Institute of Sport
Lakeside Stadium,
33 Aughtie Drive,
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Co-Investigator:
Dr. Kevin Ball
Institute for Health and Sport, Victoria University
kevin.ball@vu.edu.au

Any queries about your participation in this project may be directed to the Chief Investigator listed above.
If you have any queries or complaints about the way you have been treated, you may contact the Ethics Secretary, Victoria University Human Research Ethics Committee, Office for Research, Victoria University, PO Box 14428, Melbourne, VIC, 8001, email researchethics@vu.edu.au or phone (03) 9919 4781 or 4461.

Appendix K: Study Five recruitment flyer

Appendix L: Study Five participant consent form

CONSENT FORM FOR PARTICIPANTS INVOLVED IN RESEARCH

INFORMATION TO PARTICIPANTS:

We would like to invite you to be a part of a study looking at the way in which rowers train and how different amounts or types of training are related to rowing performance.

This study aims to investigate how different amounts and methods of training effect rowing performance over 2000 m. Participation in the study will require you to complete risk assessment and training history questionnaires to ensure you're medically fit to participate in the study. Participation will also involve having a power meter (device that sits on your rigger) on your boat to record power output (how hard you pull on the oars) and recording your heart rate from a heart rate monitor (watch and chest strap) during every training session you perform throughout this domestic rowing season (September 2019 to April 2020), including recording heart rate from any cycling and running sessions performed. You will be asked to upload your heart rate to the password protected online software TrainingPeaks. You will be asked to perform a 2000 m time trial (performed rowing as hard as possible over 2000 m) in September 2019 and December 2019 recording heart rate and power output throughout, and during 2000 m races performed at regattas in February and April 2020. You will be asked to perform an on-water step test in September 2019, December 2019 and April 2020 which will involve rowing 7 x 4-min stages starting at a low/easy intensity and progressively getting harder, with the final 4-minute stage performed as hard as possible and one-minute rest between each stage. The air you breathe out will be measured using a gas analysis system (this will involve wearing a face mask that you will breath into during the test). At the end of each 4-minute stage you will be asked to rate how hard the stage was, and a very small (pinhead size) sample of blood will be taken from your finger by a small needle prick to measure your blood lactate levels (as a measure of energy production in your body). Your heart rate and power output will also be recorded throughout the step-tests you perform. Potential risks associated with the project include the risk of other rowers and coaches knowing about your participation in this study, as the power meter equipment on your boat will be obvious to others. There is also a risk of experiencing fatigue (tiredness), muscle soreness, stiffness and soft tissue injury from rowing, a low risk of experiencing breathlessness, light-headedness, nausea, vomiting, fainting, or performance related anxiety, and a very low risk of vasovagal (heart related) episodes or sudden death following maximal exercise. There is also a risk of infection from the needle prick obtained during blood collection for lactate analysis.

CERTIFICATION BY PARTICIPANT

I, "[Click here & type participant's name]"
of "[Click here & type participant's suburb]"

I certify that I am at least 18 years old and that I am voluntarily giving my consent to participate in the study: longitudinal monitoring of training characteristics in rowing being conducted at Victoria University by: Professor Robert Aughey.

I certify that the objectives of the study, together with any risks and safeguards associated with the procedures listed hereunder to be carried out in the research, have been fully explained to me by:

Ana Holt

and that I freely consent to participation involving the below mentioned procedures:

- ☐ Completion of a risk assessment questionnaire to determine if I'm medically fit to participate
- ☐ Completion of a questionnaire regarding my recent training history
- ☐ The recording of my power output (how hard I pull on the oars) from a power meter placed on my boat, and heart rate from my wearing of a heart rate monitor throughout every training session performed this rowing season (September 2019 to April 2020)
- ☐ Uploading of my heart rate data from all training sessions performed to the password protected online software TrainingPeaks.
- ☐ Performance of 2000 m time trials (performed as hard as possible) four times throughout this rowing season, with power and heart rate collected throughout each.

- Performance of three on-water step tests involving 7 x 4-minute stages of increasing intensity from low/easy to maximum/as hard as possible, with one-minute rest between each stage.
- Collection of my expired air (breath), heart rate and power output throughout the on-water step test, as well as a small blood sample from my finger (to assess the energy production in my body) and my rating of perceived exertion (how hard the rowing felt) at the end of each 4-minute stage.

I certify that I have had the opportunity to have any questions answered and that I understand that I can withdraw from this study at any time and that this withdrawal will not jeopardise me in any way.

I certify that I am in good health and am not currently suffering from any injury or illness which may impair my physical performance, health or wellbeing.

I have been informed that the information I provide will be kept confidential.

I agree to share my data collected throughout the duration of this study with my coach (by agreeing your data will **only** be shared with the coach you specify below. You are entitled to withdraw your consent to share your data with your coach at any time. If you do not wish (or no longer wish) to share your data with your coach this will not influence your participation in the study in any way).
Coaches Name:______________________ **Yes/No** (please circle)

I agree to allow my photo to be taken during my participation in the study and any photos of me taken to be shown in presentation of the research at conferences or otherwise (all photos taken will have faces blocked out and will not be identifiable. Your decision will not influence your participation in the study in any way). **Yes/No** (please circle)

I agree to allow the use of my collected data to be used for research, including journal publications and post-graduate thesis

Signed:
Date:

Any queries about your participation in this project may be directed to the researcher
Professor Robert Aughey
61 3 9919 6329

If you have any queries or complaints about the way you have been treated, you may contact the Ethics Secretary, Victoria University Human Research Ethics Committee, Office for Research, Victoria University, PO Box 14428, Melbourne, VIC, 8001, email Researchethics@vu.edu.au or phone (03) 9919 4781 or 4461.

Appendix M: Study One and Two ethics approval letter

Wednesday, May 1, 2019 at 9:38:58 AM Australian Eastern Standard Time

Subject: Quest Ethics Notification - Application Process Finalised - Application Approved
Date: Monday, 4 June 2018 at 11:48:19 am Australian Eastern Standard Time
From: quest.noreply@vu.edu.au
To: robert.aughey@vu.edu.au
CC: Ana Holt, kevballkicking@gmail.com, rodney.siegel@vis.org.au

Dear PROF ROBERT AUGHEY,

Your ethics application has been formally reviewed and finalised.

» Application ID: HRE18-085
» Chief Investigator: PROF ROBERT AUGHEY
» Other Investigators: MS Ana Holt, DR KEVIN BALL, DR RODNEY SIEGEL
» Application Title: The validity of three rowing power meters
» Form Version: 13-07

The application has been accepted and deemed to meet the requirements of the National Health and Medical Research Council (NHMRC) 'National Statement on Ethical Conduct in Human Research (2007)' by the Victoria University Human Research Ethics Committee. Approval has been granted for two (2) years from the approval date; 04/06/2018.

Continued approval of this research project by the Victoria University Human Research Ethics Committee (VUHREC) is conditional upon the provision of a report within 12 months of the above approval date or upon the completion of the project (if earlier). A report proforma may be downloaded from the Office for Research website at: http://research.vu.edu.au/hrec.php.

Please note that the Human Research Ethics Committee must be informed of the following: any changes to the approved research protocol, project timelines, any serious events or adverse and/or unforeseen events that may affect continued ethical acceptability of the project. In these unlikely events, researchers must immediately cease all data collection until the Committee has approved the changes. Researchers are also reminded of the need to notify the approving HREC of changes to personnel in research projects via a request for a minor amendment. It should also be noted that it is the Chief Investigators' responsibility to ensure the research project is conducted in line with the recommendations outlined in the National Health and Medical Research Council (NHMRC) 'National Statement on Ethical Conduct in Human Research (2007).'

On behalf of the Committee, I wish you all the best for the conduct of the project.

Secretary, Human Research Ethics Committee
Phone: 9919 4781 or 9919 4461
Email: researchethics@vu.edu.au

This is an automated email from an unattended email address. Do not reply to this address.

Appendix N: Study Three and Four ethics approval letter

Wednesday, May 1, 2019 at 9:18:40 AM Australian Eastern Standard Time

Subject: Quest Ethics Notification - Application Process Finalised - Application Approved
Date: Tuesday, 30 April 2019 at 12:10:21 pm Australian Eastern Standard Time
From: quest.noreply@vu.edu.au
To: robert.aughey@vu.edu.au
CC: Ana Holt, kevballkicking@gmail.com, rodney.siegel@vis.org.au

Dear PROF ROBERT AUGHEY,

Your ethics application has been formally reviewed and finalised.

» Application ID: HRE19-036
» Chief Investigator: PROF ROBERT AUGHEY
» Other Investigators: MS Ana Holt, DR RODNEY SIEGEL, DR KEVIN BALL
» Application Title: Technical Determinants of On-water Rowing Performance
» Form Version: 13-07

The application has been accepted and deemed to meet the requirements of the National Health and Medical Research Council (NHMRC) 'National Statement on Ethical Conduct in Human Research (2007)' by the Victoria University Human Research Ethics Committee. Approval has been granted for two (2) years from the approval date; 30/04/2019.

Continued approval of this research project by the Victoria University Human Research Ethics Committee (VUHREC) is conditional upon the provision of a report within 12 months of the above approval date or upon the completion of the project (if earlier). A report proforma may be downloaded from the Office for Research website at: http://research.vu.edu.au/hrec.php.

Please note that the Human Research Ethics Committee must be informed of the following: any changes to the approved research protocol, project timelines, any serious events or adverse and/or unforeseen events that may affect continued ethical acceptability of the project. In these unlikely events, researchers must immediately cease all data collection until the Committee has approved the changes. Researchers are also reminded of the need to notify the approving HREC of changes to personnel in research projects via a request for a minor amendment. It should also be noted that it is the Chief Investigators' responsibility to ensure the research project is conducted in line with the recommendations outlined in the National Health and Medical Research Council (NHMRC) 'National Statement on Ethical Conduct in Human Research (2007).'

On behalf of the Committee, I wish you all the best for the conduct of the project.

Secretary, Human Research Ethics Committee
Phone: 9919 4781 or 9919 4461
Email: researchethics@vu.edu.au

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Appendix O: Study Five ethics approval letter

Wednesday, September 4, 2019 at 9:20:28 AM Australian Eastern Standard Time

Subject: Quest Ethics Notification - Application Process Finalised - Application Approved
Date: Tuesday, 3 September 2019 at 3:56:12 pm Australian Eastern Standard Time
From: quest.noreply@vu.edu.au
To: robert.aughey@vu.edu.au
CC: Ana Holt, kevballkicking@gmail.com, rodney.siegel@vis.org.au

Dear PROF ROBERT AUGHEY,

Your ethics application has been formally reviewed and finalised.

» Application ID: HRE19-106
» Chief Investigator: PROF ROBERT AUGHEY
» Other Investigators: DR KEVIN BALL, DR RODNEY SIEGEL, MS Ana Holt
» Application Title: Longitudinal monitoring of training characteristics in rowing
» Form Version: 13-07

The application has been accepted and deemed to meet the requirements of the National Health and Medical Research Council (NHMRC) 'National Statement on Ethical Conduct in Human Research (2007)' by the Victoria University Human Research Ethics Committee. Approval has been granted for two (2) years from the approval date; 03/09/2019.

Continued approval of this research project by the Victoria University Human Research Ethics Committee (VUHREC) is conditional upon the provision of a report within 12 months of the above approval date or upon the completion of the project (if earlier). A report proforma may be downloaded from the Office for Research website at: http://research.vu.edu.au/hrec.php.

Please note that the Human Research Ethics Committee must be informed of the following: any changes to the approved research protocol, project timelines, any serious events or adverse and/or unforeseen events that may affect continued ethical acceptability of the project. In these unlikely events, researchers must immediately cease all data collection until the Committee has approved the changes. Researchers are also reminded of the need to notify the approving HREC of changes to personnel in research projects via a request for a minor amendment. It should also be noted that it is the Chief Investigators' responsibility to ensure the research project is conducted in line with the recommendations outlined in the National Health and Medical Research Council (NHMRC) 'National Statement on Ethical Conduct in Human Research (2007).'

On behalf of the Committee, I wish you all the best for the conduct of the project.

Secretary, Human Research Ethics Committee
Phone: 9919 4781 or 9919 4461
Email: researchethics@vu.edu.au

This is an automated email from an unattended email address. Do not reply to this address.

Appendix P: Study One statistical analysis SAS script for systematic bias

```
*FILENAME REFFILE '/folders/myshortcuts/ExternalFiles/Projects/_VU
Melbourne/Ana Holt/S1P1 database_including oar angle data_for analysis.xlsx';
*FILENAME REFFILE '/folders/myshortcuts/ExternalFiles/Projects/_VU
Melbourne/Ana Holt/S1P1 Database (stroke side only).xlsx';

%macro rely;
PROC IMPORT DATAFILE=REFFILE
	DBMS=XLSX
	OUT=dat1 replace;
	GETNAMES=YES;
attrib _character_ _numeric_ label="";
RUN;

*proc univariate plot;

data _null_;
if &logflag then call symput('unitsrawlog',"percent");
else call symput('unitsrawlog',"raw");

data dat2;
set dat1;
*if strokeNumber>2;
*if Trial=7 then delete; *baseplate moved; *now included in subset;
*if Side="Stroke" and (Trial=7 or Trial=5 or Trial=10) then delete; *baseplate moved?;
*10 is a dud too in vhigh, for stroke side;
Device=Brand;
Position="Catch ";
Angle=PMCatchAngle;
output;
Device="Vicon";
Angle=ViconCatchAngle;
output;

Device=Brand;
Position="Finish";
Angle=PMFinishAngle;
output;
Device="Vicon";
Angle=ViconFinishAngle;
output;

Device=Brand;
Position="Arc";
Angle=PMFinishAngle-PMCatchAngle;
output;
Device="Vicon";
```

```
Angle=ViconFinishAngle-ViconCatchAngle;
output;
keep Device Side Position Angle StrokeRate Trial StrokeNumber SerialNumber;

/*
proc print data=dat2(obs=100);run;

proc freq;
tables Device*Position/nocol norow nopercent;
run;
*/

data dat3;
set dat2;
if Device="Peach" or SerialNumber<10000 then delete; *selects NK;
*if Device="NK" or SerialNumber>10000 then delete; *selects Peach;
*if Position="Catch"; * and Trial<7 and StrokeRate>30;
PeachNK=1;
if Device="Vicon" then PeachNK=0;
xVarNK=0; xVarPeach=0; xVarVicon=0;
if Device="NK" then xVarNK=1;
if Device="Peach" then xVarPeach=1;
if Device="Vicon" then xVarVicon=1;
SRgroup="1.lomod";
*if StrokeRate>22 then SRgroup="2.mod";
if StrokeRate>30 then SRgroup="3.high";
if StrokeRate>38 then SRgroup="4.vhigh";
if StrokeRate>44 then SRgroup="5.max";
xVarNKVicon=0; xVarPeachVicon=0;
if Device="NK" or Device="Vicon" then xVarNKVicon=1;
if Device="Peach" or Device="Vicon" then xVarPeachVicon=1;
SerialEndDigit=mod(SerialNumber,10);
DeviceUnit="Vicon  ";
if Device ne "Vicon" then DeviceUnit=trim(left(SerialNumber));
/*
if Device="Vicon" then do;
  SerialEndDigit=0;
  SerialNumber=0;
  end;
  */
&subset;
Angle=Angle*10;

proc sort;
by Position SRgroup;

data cov lsm lsmdiff lsmdiff1 lsmdiff2  lsmest est solf solr;
&title1;
```

```
ods select none;
ods listing close;
proc mixed data=dat3 covtest cl alpha=&alpha &nob &convcrit;
class DeviceUnit Device StrokeNumber StrokeRate Trial SRgroup  SerialNumber
SerialEndDigit;
model &dep=Device StrokeRate StrokeNumber/outp=pred s noint residual ddfm=sat;
*better without ddfm=sat;
*model &dep=Device SerialNumber(Device) StrokeRate StrokeNumber/outp=pred s
noint residual ddfm=sat; *better without ddfm=sat;
*model &dep=Device StrokeNumber Device*StrokeNumber StrokeRate/outp=pred s
noint residual ddfm=sat; *better without ddfm=sat;
*model Angle=Device PeachNK*SerialNumber(Device) StrokeRate/ddfm=sat
outp=pred s noint;
*lsmeans Device SerialNumber/cl diff alpha=&alpha;
lsmeans Device/cl diff alpha=&alpha;
/*
lsmestimate Device*SerialNumber "NK-Vicon:" 0;
lsmestimate Device*SerialNumber
  "Unit 1100827" 1 0 0 0  0 0 0  0 0 0  -1 0 0 0,
  "Unit 1101134" 0 1 0 0  0 0 0  0 0 0  0 -1 0 0,
  "Unit 1101819" 0 0 1 0  0 0 0  0 0 0  0 0 -1 0,
  "Unit 1101823" 0 0 0 1  0 0 0  0 0 0  0 0 0 -1
  /cl alpha=0.1;
lsmestimate Device*SerialNumber "Peach-Vicon:" 0;
lsmestimate Device*SerialNumber
  "Unit 2247" 0 0 0 0  1 0 0  -1 0 0,
  "Unit 2248" 0 0 0 0  0 1 0  0 -1 0,
  "Unit 2566" 0 0 0 0  0 0 1  0 0 -1
  /cl alpha=0.1;
*/
*lsmeans Device SerialNumber(Device)/cl diff alpha=&alpha;
*lsmeans StrokeRate StrokeNumber/cl alpha=&alpha;
random int/subject=StrokeNumber*StrokeRate*Trial;
random Trial;
random PeachNK*SerialNumber/Group=Device s;
*random int xVarPeach/subject=StrokeNumber*StrokeRate*Trial s;
*repeated/group=Device;
repeated/group=DeviceUnit;
&parms;
by Position SRgroup;
ods output classlevels=clev;
ods output covparms=cov;
ods output lsmeans=lsm;
ods output diffs=lsmdiff;
ods output estimates=est;
ods output solutionf=solf;
ods output solutionr=solr;
```

```
ods output lsmestimates=lsmest;
*where SRgroup="5.max" or StrokeNumber>4;
*where Position="Arc" and SRgroup="2.mod"; * and StrokeRate=32;
*where Position="Arc" and SRgroup="3.high";
*where Position="Arc" and SRgroup="4.vhigh";
*where Position="Arc" and (SRgroup="5.max" or SRgroup="4.vhigh");
*where Position="Arc" and SRgroup="5.max";
*where Position="Catch";
*where Position="Finish";
*where Position="Arc";
run;
ods select all;
ods listing;
*proc print data=lsm;run;

data cov;
set cov;
array a estimate stderr lower upper;
do over a;
  a=a/100;
  end;

data lsm;
set lsm;
array a estimate stderr lower upper;
do over a;
  a=a/10;
  end;

data lsmdiff;
set lsmdiff;
array a estimate stderr lower upper;
do over a;
  a=a/10;
  end;

data est;
set est;
array a estimate stderr lower upper;
do over a;
  a=a/10;
  end;

data lsmest;
set lsmest;
array a estimate stderr lower upper;
do over a;
  a=a/10;
```

```
  end;

data pred;
set pred;
array a &dep Pred StdErrPred lower upper resid;
do over a;
  a=a/10;
  end;

data solr;
set solr;
array a Estimate StdErrPred ;
do over a;
  a=a/10;
  end;

*proc print data=clev; run;
&title1;
title2 "Random effects, to check on adequacy of the model";
proc print data=cov noobs;
by Position SRgroup;
run;

data pred1;
set pred;
if &logflag then do;
  *pred=exp(pred/100);
  &dep=exp(&dep/100);
  end;

*proc print data=pred;run;
/*
title2 "Standardized residuals vs predicteds";
options ls=80 ps=36;
proc plot data=pred1;
plot StudentResid*pred=Device;
by Position SRgroup;
run;
*/
proc sort data=pred1;
by Position SRgroup Device;

title2 "Usual residuals vs predicteds with SerialEndDigit to check for noisy units";
title3 "(but now not an issue, separate model showed similar resids for each unit)";
options ls=80 ps=36;
proc plot data=pred1;
plot Resid*pred=SerialEndDigit;
by Position SRgroup Device;
```

```
run;

/*
proc sort data=pred1;
by Position SRgroup StrokeRate;

title2 "Usual residuals vs StrokeNumber for Trial 7 to check when slippage occurs";
options ls=80 ps=36;
proc plot data=pred1;
plot Resid*StrokeNumber;
where SerialEndDigit=3 and Device="Peach";
by Position SRgroup StrokeRate;
run;
*/
/*
title2 "SDs of residuals to check for noisy units";
title3 "which could also be due to baseplate slipping";
proc means maxdec=2 data=pred1 std min max;
var Resid;
class Position SRgroup Device SerialNumber;
run;
*/
/*
options ls=100 ps=50;
data pred2;
set pred1;
if abs(StudentResid)>4.5;

options ps=52 ls=100;
proc print data=pred2;
var Device Trial StrokeRate StrokeNumber SRgroup  SerialNumber &dep pred resid
Studentresid;
title2 "Outliers (Standardized residual >4.5)";
format &dep 5.&decdep studentresid 5.1;
by Position SRgroup;run;
option ls=90;
*/
data covall;
*length Device $ 5 Group $ 12;
set cov;
alpha=&alpha;
DegFree=2*ZValue**2;
*if Lower=. then do;
  *Lower=DegFree*estimate/CINV(1-alpha/2,DegFree);
  *Upper=DegFree*estimate/CINV(alpha/2,DegFree);
  *conf limits via normal dist;
  lower=estimate+probit(alpha/2)*StdErr;
  upper=estimate-probit(alpha/2)*StdErr;
```

```
*  end;
array a estimate lower upper;
do over a;
  a=sign(a)*sqrt(abs(a));
  end;
if &logflag=1 then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(upper-lower)/2;
*if substr(covparm,1,2) ne "UN" then CLpm=(upper-lower)/2;
CLtd=sqrt(upper/lower);
drop StdErr--ProbZ;

title2 "Random effects as standard deviations (&unitsrawlog)";
proc print noobs data=covall;
var covparm subject Group estimate CLpm lower upper alpha;
format estimate lower upper CLpm 5.&deceff CLtd 5.2 DegFree 5.0;
by Position SRgroup;
run;

title2 "MBI for random effects with a given smallest important for means of
&magnithresh (&unitsrawlog)";
data cov1;
set cov;
*if substr(Group,8)="NK" or substr(Group,8)="Peach"; *add or modify, depending on
the analysis;
*lower=estimate+probit(alpha/2)*StdErr; *for those models where nobound did not
work;
*upper=estimate-probit(alpha/2)*StdErr;
DF=999;
MagniThresh=abs(&MagniThresh)/2;
if &logflag then Magnithresh=100*exp(log(1+abs(&magnithresh)/100)/2)-100;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh)**2)/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh)**2)/StdErr,DF);
if &logflag then do;
  *if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-
(100*log(1+MagniThresh/100))**2)/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+(100*log(1+MagniThresh/100))**2)/StdErr,DF);
    end;
ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
*ClinFlag=0; *want all inferences to be non-clinical for within-subject random effect;
*mechanistic inferences;
ClearOrNot="unclear";
Prob="       ";
Magni="     ";
```

```
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then ClearOrNot="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then ClearOrNot="@99%  ";
if ClearOrNot ne "unclear" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if ClearOrNot ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
if not stderr then do; Magni="";ClearOrNot=""; end;

data cov2;
set cov1;
alpha=&alpha;
*if covparm ne "Residual" then do;
  lower=estimate+probit(alpha/2)*StdErr;
  upper=estimate-probit(alpha/2)*StdErr;
*  end;
array a estimate lower upper;
do over a;
  a=sign(a)*sqrt(abs(a));
  end;
DegFree=2*Zvalue**2;
array r SD lower upper;
if &logflag=1 then do over r;
  r=100*exp(r/100)-100;
  end;
CLpm=(upper-lower)/2;
*if substr(covparm,1,2) ne "UN" then CLpm=(upper-lower)/2;
CLtd=sqrt(upper/lower);
run;

title3 "Non-clinical inferences for SD representing random effects";
title4 "Magnithresh is half the given smallest difference for means";
proc print data=cov2 noobs;
var covparm subject Group estimate CLpm lower upper alpha
  MagniThresh ChanceNeg ChanceTriv ChancePos Prob Magni ClearOrNot;
format estimate CLpm lower upper MagniThresh 5.&deceff ChanceNeg ChanceTriv
  ChancePos 5.1 DF 5.0;
```

```
by Position SRgroup;
run;

title2 "Random-effect solution representing differences in means for the different units
from overall device mean";
title3 "These may help identify units with consistent bias.";
data solr1;
set solr;
if Device ne "" and Device ne "Vicon";
Alpha=&alpha;
t=tinv(1-&alpha/2,DF);
LowerCL=Estimate-t*StdErrPred;
UpperCL=Estimate+t*StdErrPred;
CLpm=(UpperCL-LowerCL)/2;

proc print noobs;
var Position SRgroup Device SerialNumber Estimate LowerCL UpperCL CLpm Alpha;
by Position SRgroup;
format Estimate LowerCL UpperCL CLpm 5.1;
run;

*proc print data=cov;run;

data lsm1;
set lsm ;
array a estimate lower upper;
if &logflag=1 then do over a;
  *a=100*exp(a/100)-100; *for modeling of change scores;
  a=exp(a/100);
  end;
CLpm=(upper-lower)/2;
drop Effect StdErr tValue Probt;

title2 "Least-squares means (raw)";
options ls=80 ps=82;
proc print data=lsm1 noobs;
var Position SRgroup Device estimate lower upper CLpm DF;
format estimate lower upper CLpm 5.&decdep;
by Position SRgroup;
run;
options ps=52;


data lsmdiff1;
set lsmdiff;
array a estimate lower upper;
if &logflag=1 then do over a;
  a=100*exp(a/100)-100;
```

```
  end;
CLpm=(upper-lower)/2;
drop stderr tValue probt;

options ps=80;
title2 "Least-squares mean differences (&unitsrawlog)";
proc print data=lsmdiff1 noobs;
var  Position SRgroup Device _Device Estimate--CLpm;
format estimate CLpm lower upper 5.&deceff DF 5.0 Probt best5.;
*where &logflag=0;
*by Position SRgroup;
*where Effect="Device" or Effect="SerialNumber(Device)" and Device=_Device;
run;

title2 "MBI for least-square mean diffs with a given smallest important for means of
&magnithresh (&unitsrawlog)";
data lsmdiff1;
set lsmdiff;
*if index("&dep","Ratio") or "&dep"="TrainPerfPercent"; *measures where lsmeans
are differences from coach prescription;
length Prob $ 8 Magni $ 4;
MagniThresh=&MagniThresh;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh))/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh))/StdErr,DF);
if &LogFlag=1 then do;
  if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  else do;
    ChancePos=100*(1-ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  end;
ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
ClinFlag=1; *want all inferences to be clinical initially;
*if index(label,"2SD") then ClinFlag=0; *covariates definitely need to be non-clinical;

*clinical inferences;
if clinflag then do;
ChPos=ChancePos; ChNeg=ChanceNeg;
if MagniThresh<0 then do;
  ChPos=ChanceNeg; ChNeg=ChancePos;
  end;
Prob=""; Magni=""; ClearOrNot="unclear";
if ChNeg<0.5 then do;
```

```
  ClearOrNot="@25/.5%";
  if ChNeg<0.1 then ClearOrNot="@5/.1% ";
  if ChanceTriv>25 then Magni="triv";
  if ChPos>25 then Magni="bene";
  Prob="possibly";
  if ChPos>75 or ChanceTriv>75 then Prob="likely  ";
  if ChPos>95 or ChanceTriv>95 then Prob="v.likely";
  if ChPos>99.5 or ChanceTriv>99.5 then Prob="m.likely";
  end;
else do; *i.e., ChNeg>0.5;
  if ChPos<25 then do;
    ClearOrNot="@25/.5%";
    if ChPos<5 then ClearOrNot="@5/.1% ";
    if ChanceTriv>25 then Magni="triv";
    if ChNeg>25 then Magni="harm";
    Prob="possibly";
    if ChNeg>75 or ChanceTriv>75 then Prob="likely  ";
    if ChNeg>95 or ChanceTriv>95 then Prob="v.likely";
    if ChNeg>99.5 or ChanceTriv>99.5 then Prob="m.likely";
    end;
  end;
if ClearOrNot="unclear" and
  (MagniThresh>0 and ORPosNeg>25/75/(0.5/99.5) or MagniThresh<0 and
ORNegPos>25/75/(0.5/99.5))
  then do;
  ClearOrNot="OR>66.3";
  Magni="bene";
  if ChPos>25 then Prob="possibly";
  if ChPos>75 then Prob="likely  ";
  if ChPos>95 then Prob="v.likely";
  if ChPos>99.5 then Prob="m.likely";
  end;
output;
end;

*mechanistic inferences;
ClinFlag=0;
ClearOrNot="unclear";
Prob="";
Magni="";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then ClearOrNot="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then ClearOrNot="@99%  ";
if ClearOrNot ne "unclear" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
```

```
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if ClearOrNot ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
*end;
output;

data lsmdiff2;
Units="Raw";
if &logflag then Units="%";
set lsmdiff1;
if estimate=0 then do;
  estimate=.; magnithresh=.; magni=""; clearornot=""; Prob=""; Units="";
  end;
array a estimate lower upper;
if &logflag then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(Upper-lower)/2;
rename df=DegFree;
run;

*options ls=135 ps=80;
title3 "Non-clinical inferences";
title4 "Magnithresh is the given smallest important difference for means";
title5 "Units for estimates, confidence limits and smallest important are &unitsrawlog";
proc print data=lsmdiff2 noobs;
where clinflag=0;
var Position SRgroup Device _Device Units estimate CLpm lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos Prob Magni ClearOrNot;
format estimate CLpm lower upper MagniThresh 5.&deceff Probt best5. ChanceNeg
ChanceTriv
  ChancePos 5.1 DegFree 5.0;
*by Position SRgroup;
*where clinflag=0 and (Effect="Device" or Effect="SerialNumber(Device)" and
Device=_Device);
run;

/*
*lsmestimates;
data lsmest1;
set lsmest;
```

```
array a estimate lower upper;
if &logflag=1 then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(upper-lower)/2;
if estimate=0 then do; estimate=.; DF=.; end;
drop stderr tValue probt;

options ps=80;
title2 "Least-squares mean estimates (&unitsrawlog)";
proc print data=lsmest1 noobs;
var Position SRgroup Label Estimate--CLpm;
format estimate CLpm lower upper 5.&deceff DF 5.0 Probt best5.;
*where &logflag=0;
*by Position SRgroup;
*where Effect="Device" or Effect="SerialNumber(Device)" and Device=_Device;
run;

title2 "MBI for least-square mean estimates with a given smallest important for means
of &magnithresh (&unitsrawlog)";
data lsmest1;
set lsmest;
*if index("&dep","Ratio") or "&dep"="TrainPerfPercent"; *measures where lsmeans
are differences from coach prescription;
length Prob $ 8 Magni $ 4;
MagniThresh=&MagniThresh;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh))/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh))/StdErr,DF);
if &LogFlag=1 then do;
  if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  else do;
    ChancePos=100*(1-ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  end;
ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
ClinFlag=1; *want all inferences to be clinical initially;
*if index(label,"2SD") then ClinFlag=0; *covariates definitely need to be non-clinical;

*clinical inferences;
if clinflag then do;
ChPos=ChancePos; ChNeg=ChanceNeg;
if MagniThresh<0 then do;
```

```
  ChPos=ChanceNeg; ChNeg=ChancePos;
  end;
Prob=""; Magni=""; ClearOrNot="unclear";
if ChNeg<0.5 then do;
  ClearOrNot="@25/.5%";
  if ChNeg<0.1 then ClearOrNot="@5/.1% ";
  if ChanceTriv>25 then Magni="triv";
  if ChPos>25 then Magni="bene";
  Prob="possibly";
  if ChPos>75 or ChanceTriv>75 then Prob="likely  ";
  if ChPos>95 or ChanceTriv>95 then Prob="v.likely";
  if ChPos>99.5 or ChanceTriv>99.5 then Prob="m.likely";
  end;
else do; *i.e., ChNeg>0.5;
  if ChPos<25 then do;
    ClearOrNot="@25/.5%";
    if ChPos<5 then ClearOrNot="@5/.1% ";
    if ChanceTriv>25 then Magni="triv";
    if ChNeg>25 then Magni="harm";
    Prob="possibly";
    if ChNeg>75 or ChanceTriv>75 then Prob="likely  ";
    if ChNeg>95 or ChanceTriv>95 then Prob="v.likely";
    if ChNeg>99.5 or ChanceTriv>99.5 then Prob="m.likely";
    end;
  end;
if ClearOrNot="unclear" and
  (MagniThresh>0 and ORPosNeg>25/75/(0.5/99.5) or MagniThresh<0 and
ORNegPos>25/75/(0.5/99.5))
  then do;
  ClearOrNot="OR>66.3";
  Magni="bene";
  if ChPos>25 then Prob="possibly";
  if ChPos>75 then Prob="likely  ";
  if ChPos>95 then Prob="v.likely";
  if ChPos>99.5 then Prob="m.likely";
  end;
output;
end;

*mechanistic inferences;
ClinFlag=0;
ClearOrNot="unclear";
Prob="";
Magni="";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then ClearOrNot="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then ClearOrNot="@99%  ";
if ClearOrNot ne "unclear" then do;
```

```
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if ClearOrNot ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
*end;
output;


data lsmest2;
Units="Raw";
if &logflag then Units="%";
set lsmest1;
if estimate=0 then do;
  estimate=.; magnithresh=.; magni=""; clearornot=""; Prob=""; Units="";
  end;
array a estimate lower upper;
if &logflag then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(Upper-lower)/2;
rename df=DegFree;
run;

*options ls=135 ps=80;
title3 "Non-clinical inferences";
title4 "Magnithresh is the given smallest important difference for means";
title5 "Units for estimates, confidence limits and smallest important are &unitsrawlog";
proc print data=lsmest2 noobs;
where clinflag=0;
var Position SRgroup Label Units estimate CLpm lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos Prob Magni ClearOrNot;
format estimate CLpm lower upper MagniThresh 5.&deceff Probt best5. ChanceNeg
ChanceTriv
  ChancePos 5.1 DegFree 5.0;
*by Position SRgroup;
*where clinflag=0 and (Effect="Device" or Effect="SerialNumber(Device)" and
Device=_Device);
run;
```

```
*/
run;
%mend;

%let alpha=0.1;
%let dep=Angle;
%let decdep=1;
%let logflag=0;
%let deceff=1;
%let nob=;
*%let nob=nobound;
%let convcrit=CONVH=1E-8 convf=1E-8;
%let StdzedMagniThresh=0.20; *smallest stdized beneficial change;
%let MagniThresh=0.5; *smallest beneficial change, in percent units, if log trans used;

*all these with angle*10, then rejig the datasets straight after proc mixed;
FILENAME REFFILE '/folders/myshortcuts/ExternalFiles/Projects/_VU
Melbourne/Ana Holt/S1P1 Database (stroke side only).xlsx';

%let subset=if Side='Stroke' and Position='Catch';
%let title1=title1 "&dep; &subset; random serial";
%let convcrit=CONVH=1E-5 convf=1E-5;
*%let convcrit=CONVH=1E-7 convf=1E-7;
%let parms=parms 250  80 20 0  100 100 100 100  1/hold=9; *did the lot!;
%rely;

%let subset=if Side='Stroke' and Position='Finish';
%let title1=title1 "&dep; &subset; random serial";
%let convcrit=CONVH=1E-5 convf=1E-5;
*%let convcrit=CONVH=1E-6 convf=1E-6;
%let parms=parms 15  20 130 0  40 40 50 50  1/hold=9; *all OK;
%rely;

%let subset=if Side='Stroke' and Position='Arc';
%let title1=title1 "&dep; &subset; random serial";
%let convcrit=CONVH=1E-5 convf=1E-5;
%let convcrit=CONVH=1E-6 convf=1E-6;
%let parms=parms 250  80 20 0  100 100 100 100  1/hold=9; *2nd and 4th;
%let parms=parms 500  400 150 0  10000 800 800 800  1/hold=9; all OK;
%rely;

*now run with bowside imported;
FILENAME REFFILE '/folders/myshortcuts/ExternalFiles/Projects/_VU
Melbourne/Ana Holt/S1P1 database_including oar angle data_for analysis.xlsx';

%let subset=if Side='Bow' and Position='Catch';
%let title1=title1 "&dep; &subset; random serial";
%let convcrit=CONVH=1E-5 convf=1E-5;
```

```
*%let convcrit=CONVH=1E-7 convf=1E-7;
%let parms=parms 250  80 20 0  100 100 100 100  1/hold=9; *did the lot!;
%rely;

%let subset=if Side='Bow' and Position='Finish';
%let title1=title1 "&dep; &subset; random serial";
%let convcrit=CONVH=1E-5 convf=1E-5;
*%let convcrit=CONVH=1E-6 convf=1E-6;
%let parms=parms 15  20 130 0  40 40 50 50  1/hold=9; *all OK;
%rely;

%let subset=if Side='Bow' and Position='Arc';
%let title1=title1 "&dep; &subset; random serial";
%let convcrit=CONVH=1E-5 convf=1E-5;
%let convcrit=CONVH=1E-6 convf=1E-6;
%let parms=parms 250  80 20 0  100 100 100 100  1/hold=9; *all OK;
%rely;
```

Appendix Q: Study One statistical analysis SAS script for random error

```
*FILENAME REFFILE '/folders/myshortcuts/ExternalFiles/Projects/_VU
Melbourne/Ana Holt/S1P1 database_including oar angle data_for analysis.xlsx';
*FILENAME REFFILE '/folders/myshortcuts/ExternalFiles/Projects/_VU
Melbourne/Ana Holt/S1P1 Database (stroke side only).xlsx';

%macro rely;
PROC IMPORT DATAFILE=REFFILE
	DBMS=XLSX
	OUT=dat1 replace;
	GETNAMES=YES;
attrib _character_ _numeric_ label="";
RUN;

*proc univariate plot;

data _null_;
if &logflag then call symput('unitsrawlog',"percent");
else call symput('unitsrawlog',"raw");

data dat2;
set dat1;
*if strokeNumber>2;
*if Trial=7 then delete; *baseplate moved; *now included in subset;
*if Side="Stroke" and (Trial=7 or Trial=5 or Trial=10) then delete; *baseplate moved?;
*10 is a dud too in vhigh, for stroke side;
Device=Brand;
Position="Catch ";
Angle=PMCatchAngle;
output;
Device="Vicon";
Angle=ViconCatchAngle;
output;

Device=Brand;
Position="Finish";
Angle=PMFinishAngle;
output;
Device="Vicon";
Angle=ViconFinishAngle;
output;

Device=Brand;
Position="Arc";
Angle=PMFinishAngle-PMCatchAngle;
output;
Device="Vicon";
```

```
Angle=ViconFinishAngle-ViconCatchAngle;
output;
keep Device Side Position Angle StrokeRate Trial StrokeNumber SerialNumber;

/*
proc print data=dat2(obs=100);run;

proc freq;
tables Device*Position/nocol norow nopercent;
run;
*/

data dat3;
set dat2;
*if Device="NK" or SerialNumber>10000 then delete;
if Device="NK" or SerialNumber>10000;
*if Position="Catch"; * and Trial<7 and StrokeRate>30;
PeachNK=1;
if Device="Vicon" then PeachNK=0;
xVarNK=0; xVarPeach=0; xVarVicon=0;
if Device="NK" then xVarNK=1;
if Device="Peach" then xVarPeach=1;
if Device="Vicon" then xVarVicon=1;
SRgroup="1.lomod";
*if StrokeRate>22 then SRgroup="2.mod";
if StrokeRate>30 then SRgroup="3.high";
if StrokeRate>38 then SRgroup="4.vhigh";
if StrokeRate>44 then SRgroup="5.max";
xVarNKVicon=0; xVarPeachVicon=0;
if Device="NK" or Device="Vicon" then xVarNKVicon=1;
if Device="Peach" or Device="Vicon" then xVarPeachVicon=1;
SerialEndDigit=mod(SerialNumber,10);
DeviceUnit="Vicon  ";
if Device ne "Vicon" then DeviceUnit=trim(left(SerialNumber));
/*
if Device="Vicon" then do;
  SerialEndDigit=0;
  SerialNumber=0;
  end;
  */
&subset;
Angle=Angle*10;

proc sort;
by Position SRgroup;

data cov lsm lsmdiff lsmdiff1 lsmdiff2  lsmest est solf solr;
&title1;
```

```
ods select none;
ods listing close;
proc mixed data=dat3 covtest cl alpha=&alpha &nob &convcrit;
class DeviceUnit Device StrokeNumber StrokeRate Trial SRgroup  SerialNumber
SerialEndDigit;
model &dep=Device SerialNumber Device*SerialNumber StrokeRate
StrokeNumber/outp=pred s noint residual ddfm=sat; *better without ddfm=sat;
*model &dep=Device SerialNumber(Device) StrokeRate StrokeNumber/outp=pred s
noint residual ddfm=sat; *better without ddfm=sat;
*model &dep=Device StrokeNumber Device*StrokeNumber StrokeRate/outp=pred s
noint residual ddfm=sat; *better without ddfm=sat;
*model Angle=Device PeachNK*SerialNumber(Device) StrokeRate/ddfm=sat
outp=pred s noint;
*lsmeans Device SerialNumber/cl diff alpha=&alpha;
lsmeans Device/cl diff alpha=&alpha;
lsmestimate Device*SerialNumber "NK-Vicon:" 0;
lsmestimate Device*SerialNumber
  "Unit 1100827" 1 0 0 0  -1 0 0 0,
  "Unit 1101134" 0 1 0 0  0 -1 0 0,
  "Unit 1101819" 0 0 1 0  0 0 -1 0,
  "Unit 1101823" 0 0 0 1  0 0 0 -1
  /cl alpha=0.1;
*lsmeans Device SerialNumber(Device)/cl diff alpha=&alpha;
*lsmeans StrokeRate StrokeNumber/cl alpha=&alpha;
random int/subject=StrokeNumber*StrokeRate*Trial s;
*random PeachNK*SerialNumber/Group=Device s;
*random int xVarPeach/subject=StrokeNumber*StrokeRate*Trial s;
repeated/group=Device;
*repeated/group=DeviceUnit;
&parms;
by Position SRgroup;
ods output classlevels=clev;
ods output covparms=cov;
ods output lsmeans=lsm;
ods output diffs=lsmdiff;
ods output estimates=est;
ods output solutionf=solf;
ods output solutionr=solr;
ods output lsmestimates=lsmest;
*where SRgroup="5.max" or StrokeNumber>4;
*where Position="Arc" and SRgroup="2.mod"; * and StrokeRate=32;
*where Position="Arc" and SRgroup="3.high";
*where Position="Arc" and SRgroup="4.vhigh";
*where Position="Arc" and (SRgroup="5.max" or SRgroup="4.vhigh");
*where Position="Arc" and SRgroup="5.max";
*where Position="Catch";
*where Position="Finish";
```

```
*where Position="Arc";
run;
ods select all;
ods listing;
*proc print data=lsm;run;

data cov;
set cov;
array a estimate stderr lower upper;
do over a;
  a=a/100;
  end;

data lsm;
set lsm;
array a estimate stderr lower upper;
do over a;
  a=a/10;
  end;

data lsmdiff;
set lsmdiff;
array a estimate stderr lower upper;
do over a;
  a=a/10;
  end;

data est;
set est;
array a estimate stderr lower upper;
do over a;
  a=a/10;
  end;

data lsmest;
set lsmest;
array a estimate stderr lower upper;
do over a;
  a=a/10;
  end;

data pred;
set pred;
array a &dep Pred StdErrPred lower upper resid;
do over a;
  a=a/10;
  end;
```

```
*proc print data=clev; run;
&title1;
title2 "Random effects, to check on adequacy of the model";
proc print data=cov noobs;
by Position SRgroup;
run;

data pred1;
set pred;
if &logflag then do;
  *pred=exp(pred/100);
  &dep=exp(&dep/100);
  end;

*proc print data=pred;run;
/*
title2 "Standardized residuals vs predicteds";
options ls=80 ps=36;
proc plot data=pred1;
plot StudentResid*pred=Device;
by Position SRgroup;
run;
*/
proc sort data=pred1;
by Position SRgroup Device;

title2 "Usual residuals vs predicteds with SerialEndDigit to check for noisy units";
title3 "(but now not an issue, separate model showed similar resids for each unit)";
options ls=80 ps=36;
proc plot data=pred1;
plot Resid*pred=SerialEndDigit;
by Position SRgroup Device;
run;

/*
proc sort data=pred1;
by Position SRgroup StrokeRate;

title2 "Usual residuals vs StrokeNumber for Trial 7 to check when slippage occurs";
options ls=80 ps=36;
proc plot data=pred1;
plot Resid*StrokeNumber;
where SerialEndDigit=3 and Device="Peach";
by Position SRgroup StrokeRate;
run;
*/
/*
title2 "SDs of residuals to check for noisy units";
```

```
title3 "which could also be due to baseplate slipping";
proc means maxdec=2 data=pred1 std min max;
var Resid;
class Position SRgroup Device SerialNumber;
run;
*/
/*
title2 "Random-effect solution for xVarNK and xVarPeach";
data solr1;
set solr;
if Effect="xVarNK" or Effect="xVarPeach";
if Effect="xVarNK" then Device="NK   ";
if Effect="xVarPeach" then Device="Peach";
if Estimate ne 0;
drop Effect StdErrPred--Probt;

proc sort;
by Position SRgroup Device Trial StrokeRate StrokeNumber;

proc sort data=dat3;
by Position SRgroup Device Trial StrokeRate StrokeNumber;

data solr2;
merge solr1(in=a) dat3(keep=Position SRgroup Device Trial StrokeRate StrokeNumber
Angle SerialNumber SerialEndDigit);
by Position SRgroup Device Trial StrokeRate StrokeNumber;
if a;

title3 "Simple stats of the solution data=solr2";
proc means maxdec=1 n mean std var;
var Estimate;
class Position SRgroup Device;
run;

*proc print data=cov;run;
*/
/*
options ls=100 ps=50;
data pred2;
set pred1;
if abs(StudentResid)>4.5;

options ps=52 ls=100;
proc print data=pred2;
var Device Trial StrokeRate StrokeNumber SRgroup  SerialNumber &dep pred resid
Studentresid;
title2 "Outliers (Standardized residual >4.5)";
format &dep 5.&decdep studentresid 5.1;
```

```
by Position SRgroup;run;
option ls=90;
*/
data covall;
*length Device $ 5 Group $ 12;
set cov;
alpha=&alpha;
DegFree=2*ZValue**2;
*if Lower=. then do;
  *Lower=DegFree*estimate/CINV(1-alpha/2,DegFree);
  *Upper=DegFree*estimate/CINV(alpha/2,DegFree);
  *conf limits via normal dist;
  lower=estimate+probit(alpha/2)*StdErr;
  upper=estimate-probit(alpha/2)*StdErr;
*  end;
array a estimate lower upper;
do over a;
  a=sign(a)*sqrt(abs(a));
  end;
if &logflag=1 then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(upper-lower)/2;
*if substr(covparm,1,2) ne "UN" then CLpm=(upper-lower)/2;
CLtd=sqrt(upper/lower);
drop StdErr--ProbZ;

title2 "Random effects as standard deviations (&unitsrawlog)";
proc print noobs data=covall;
var covparm subject Group estimate CLtd CLpm lower upper alpha;
format estimate lower upper CLpm 5.&deceff CLtd 5.2 DegFree 5.0;
by Position SRgroup;
run;

title2 "MBI for random effects with a given smallest important for means of
&magnithresh (&unitsrawlog)";
data cov1;
set cov;
*if substr(Group,8)="NK" or substr(Group,8)="Peach"; *add or modify, depending on
the analysis;
*lower=estimate+probit(alpha/2)*StdErr; *for those models where nobound did not
work;
*upper=estimate-probit(alpha/2)*StdErr;
DF=999;
MagniThresh=abs(&MagniThresh)/2;
if &logflag then Magnithresh=100*exp(log(1+abs(&magnithresh)/100)/2)-100;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh)**2)/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh)**2)/StdErr,DF);
```

```
if &logflag then do;
  *if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-
(100*log(1+MagniThresh/100))**2)/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+(100*log(1+MagniThresh/100))**2)/StdErr,DF);
    end;
ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
*ClinFlag=0; *want all inferences to be non-clinical for within-subject random effect;
*mechanistic inferences;
ClearOrNot="unclear";
Prob="        ";
Magni="     ";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then ClearOrNot="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then ClearOrNot="@99%  ";
if ClearOrNot ne "unclear" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if ClearOrNot ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
if not stderr then do; Magni="";ClearOrNot=""; end;

data cov2;
set cov1;
alpha=&alpha;
*if covparm ne "Residual" then do;
  lower=estimate+probit(alpha/2)*StdErr;
  upper=estimate-probit(alpha/2)*StdErr;
*  end;
array a estimate lower upper;
do over a;
  a=sign(a)*sqrt(abs(a));
  end;
DegFree=2*Zvalue**2;
array r SD lower upper;
if &logflag=1 then do over r;
```

```
  r=100*exp(r/100)-100;
  end;
CLpm=(upper-lower)/2;
*if substr(covparm,1,2) ne "UN" then CLpm=(upper-lower)/2;
CLtd=sqrt(upper/lower);
run;

title3 "Non-clinical inferences for SD representing random effects";
title4 "Magnithresh is half the given smallest difference for means";
proc print data=cov2 noobs;
var covparm subject Group estimate CLpm lower upper alpha
  MagniThresh ChanceNeg ChanceTriv ChancePos Prob Magni ClearOrNot;
format estimate CLpm lower upper MagniThresh 5.&deceff ChanceNeg ChanceTriv
  ChancePos 5.1 DF 5.0;
by Position SRgroup;
run;

data lsm1;
set lsm ;
array a estimate lower upper;
if &logflag=1 then do over a;
  *a=100*exp(a/100)-100; *for modeling of change scores;
  a=exp(a/100);
  end;
CLpm=(upper-lower)/2;
drop Effect StdErr tValue Probt;

title2 "Least-squares means (raw)";
options ls=80 ps=82;
proc print data=lsm1 noobs;
var Position SRgroup Device estimate lower upper CLpm DF;
format estimate lower upper CLpm 5.&decdep;
by Position SRgroup;
run;
options ps=52;


data lsmdiff1;
set lsmdiff;
array a estimate lower upper;
if &logflag=1 then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(upper-lower)/2;
drop stderr tValue probt;

options ps=80;
title2 "Least-squares mean differences (&unitsrawlog)";
```

```
proc print data=lsmdiff1 noobs;
var  Position SRgroup Device _Device Estimate--CLpm;
format estimate CLpm lower upper 5.&deceff DF 5.0 Probt best5.;
*where &logflag=0;
*by Position SRgroup;
*where Effect="Device" or Effect="SerialNumber(Device)" and Device=_Device;
run;

title2 "MBI for least-square mean diffs with a given smallest important for means of
&magnithresh (&unitsrawlog)";
data lsmdiff1;
set lsmdiff;
*if index("&dep","Ratio") or "&dep"="TrainPerfPercent"; *measures where lsmeans
are differences from coach prescription;
length Prob $ 8 Magni $ 4;
MagniThresh=&MagniThresh;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh))/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh))/StdErr,DF);
if &LogFlag=1 then do;
  if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  else do;
    ChancePos=100*(1-ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  end;
ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
ClinFlag=1; *want all inferences to be clinical initially;
*if index(label,"2SD") then ClinFlag=0; *covariates definitely need to be non-clinical;

*clinical inferences;
if clinflag then do;
ChPos=ChancePos; ChNeg=ChanceNeg;
if MagniThresh<0 then do;
  ChPos=ChanceNeg; ChNeg=ChancePos;
  end;
Prob=""; Magni=""; ClearOrNot="unclear";
if ChNeg<0.5 then do;
  ClearOrNot="@25/.5%";
  if ChNeg<0.1 then ClearOrNot="@5/.1% ";
  if ChanceTriv>25 then Magni="triv";
  if ChPos>25 then Magni="bene";
  Prob="possibly";
  if ChPos>75 or ChanceTriv>75 then Prob="likely  ";
```

```
  if ChPos>95 or ChanceTriv>95 then Prob="v.likely";
  if ChPos>99.5 or ChanceTriv>99.5 then Prob="m.likely";
  end;
else do; *i.e., ChNeg>0.5;
  if ChPos<25 then do;
    ClearOrNot="@25/.5%";
    if ChPos<5 then ClearOrNot="@5/.1% ";
    if ChanceTriv>25 then Magni="triv";
    if ChNeg>25 then Magni="harm";
    Prob="possibly";
    if ChNeg>75 or ChanceTriv>75 then Prob="likely  ";
    if ChNeg>95 or ChanceTriv>95 then Prob="v.likely";
    if ChNeg>99.5 or ChanceTriv>99.5 then Prob="m.likely";
    end;
  end;
if ClearOrNot="unclear" and
  (MagniThresh>0 and ORPosNeg>25/75/(0.5/99.5) or MagniThresh<0 and
ORNegPos>25/75/(0.5/99.5))
  then do;
  ClearOrNot="OR>66.3";
  Magni="bene";
  if ChPos>25 then Prob="possibly";
  if ChPos>75 then Prob="likely  ";
  if ChPos>95 then Prob="v.likely";
  if ChPos>99.5 then Prob="m.likely";
  end;
output;
end;

*mechanistic inferences;
ClinFlag=0;
ClearOrNot="unclear";
Prob="";
Magni="";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then ClearOrNot="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then ClearOrNot="@99%  ";
if ClearOrNot ne "unclear" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if ClearOrNot ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
```

```
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
*end;
output;

data lsmdiff2;
Units="Raw";
if &logflag then Units="%";
set lsmdiff1;
if estimate=0 then do;
  estimate=.; magnithresh=.; magni=""; clearornot=""; Prob=""; Units="";
  end;
array a estimate lower upper;
if &logflag then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(Upper-lower)/2;
rename df=DegFree;
run;

*options ls=135 ps=80;
title3 "Non-clinical inferences";
title4 "Magnithresh is the given smallest important difference for means";
title5 "Units for estimates, confidence limits and smallest important are &unitsrawlog";
proc print data=lsmdiff2 noobs;
where clinflag=0;
var SRgroup Device _Device Units estimate CLpm lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos Prob Magni ClearOrNot;
format estimate CLpm lower upper MagniThresh 5.&deceff Probt best5. ChanceNeg
ChanceTriv
  ChancePos 5.1 DegFree 5.0;
*by Position SRgroup;
*where clinflag=0 and (Effect="Device" or Effect="SerialNumber(Device)" and
Device=_Device);
run;

*lsmestimates;
data lsmest1;
set lsmest;
array a estimate lower upper;
if &logflag=1 then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(upper-lower)/2;
if estimate=0 then do; estimate=.; DF=.; end;
drop stderr tValue probt;
```

```
options ps=80;
title2 "Least-squares mean estimates (&unitsrawlog)";
proc print data=lsmest1 noobs;
var Position SRgroup Label Estimate--CLpm;
format estimate CLpm lower upper 5.&deceff DF 5.0 Probt best5.;
*where &logflag=0;
*by Position SRgroup;
*where Effect="Device" or Effect="SerialNumber(Device)" and Device=_Device;
run;

title2 "MBI for least-square mean estimates with a given smallest important for means
of &magnithresh (&unitsrawlog)";
data lsmest1;
set lsmest;
*if index("&dep","Ratio") or "&dep"="TrainPerfPercent"; *measures where lsmeans
are differences from coach prescription;
length Prob $ 8 Magni $ 4;
MagniThresh=&MagniThresh;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh))/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh))/StdErr,DF);
if &LogFlag=1 then do;
  if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  else do;
    ChancePos=100*(1-ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  end;
ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
ClinFlag=1; *want all inferences to be clinical initially;
*if index(label,"2SD") then ClinFlag=0; *covariates definitely need to be non-clinical;

*clinical inferences;
if clinflag then do;
ChPos=ChancePos; ChNeg=ChanceNeg;
if MagniThresh<0 then do;
  ChPos=ChanceNeg; ChNeg=ChancePos;
  end;
Prob=""; Magni=""; ClearOrNot="unclear";
if ChNeg<0.5 then do;
  ClearOrNot="@25/.5%";
  if ChNeg<0.1 then ClearOrNot="@5/.1% ";
  if ChanceTriv>25 then Magni="triv";
```

```
  if ChPos>25 then Magni="bene";
  Prob="possibly";
  if ChPos>75 or ChanceTriv>75 then Prob="likely  ";
  if ChPos>95 or ChanceTriv>95 then Prob="v.likely";
  if ChPos>99.5 or ChanceTriv>99.5 then Prob="m.likely";
  end;
else do; *i.e., ChNeg>0.5;
  if ChPos<25 then do;
    ClearOrNot="@25/.5%";
    if ChPos<5 then ClearOrNot="@5/.1% ";
    if ChanceTriv>25 then Magni="triv";
    if ChNeg>25 then Magni="harm";
    Prob="possibly";
    if ChNeg>75 or ChanceTriv>75 then Prob="likely  ";
    if ChNeg>95 or ChanceTriv>95 then Prob="v.likely";
    if ChNeg>99.5 or ChanceTriv>99.5 then Prob="m.likely";
    end;
  end;
if ClearOrNot="unclear" and
  (MagniThresh>0 and ORPosNeg>25/75/(0.5/99.5) or MagniThresh<0 and
ORNegPos>25/75/(0.5/99.5))
  then do;
  ClearOrNot="OR>66.3";
  Magni="bene";
  if ChPos>25 then Prob="possibly";
  if ChPos>75 then Prob="likely  ";
  if ChPos>95 then Prob="v.likely";
  if ChPos>99.5 then Prob="m.likely";
  end;
output;
end;

*mechanistic inferences;
ClinFlag=0;
ClearOrNot="unclear";
Prob="";
Magni="";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then ClearOrNot="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then ClearOrNot="@99%  ";
if ClearOrNot ne "unclear" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
```

```
  end;
if ClearOrNot ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
*end;
output;

data lsmest2;
Units="Raw";
if &logflag then Units="%";
set lsmest1;
if estimate=0 then do;
  estimate=.; magnithresh=.; magni=""; clearornot=""; Prob=""; Units="";
  end;
array a estimate lower upper;
if &logflag then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(Upper-lower)/2;
rename df=DegFree;
run;

*options ls=135 ps=80;
title3 "Non-clinical inferences";
title4 "Magnithresh is the given smallest important difference for means";
title5 "Units for estimates, confidence limits and smallest important are &unitsrawlog";
proc print data=lsmest2 noobs;
where clinflag=0;
var Position SRgroup Label Units estimate CLpm lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos Prob Magni ClearOrNot;
format estimate CLpm lower upper MagniThresh 5.&deceff Probt best5. ChanceNeg
ChanceTriv
  ChancePos 5.1 DegFree 5.0;
*by Position SRgroup;
*where clinflag=0 and (Effect="Device" or Effect="SerialNumber(Device)" and
Device=_Device);
run;

*proc print data=lsmest;
*by Position SRgroup;
run;
%mend;

%let alpha=0.1;
%let dep=Angle;
```

```
%let decdep=1;
%let logflag=0;
%let deceff=1;
%let nob=;
*%let nob=nobound;
%let convcrit=CONVH=1E-8 convf=1E-8;
%let StdzedMagniThresh=0.20; *smallest stdized beneficial change;
%let MagniThresh=0.5; *smallest beneficial change, in percent units, if log trans used;


*all these with angle*10, then rejig the datasets straight after proc mixed;
FILENAME REFFILE '/folders/myshortcuts/ExternalFiles/Projects/_VU
Melbourne/Ana Holt/S1P1 Database (stroke side only).xlsx';

%let subset=if Side='Stroke' and Position='Catch' and Trial ne 5 and Trial ne 10 and
Trial ne 7;
%let title1=title1 "&dep; &subset; fixed serial";
%let convcrit=CONVH=1E-6 convf=1E-6;
*%let parms=parms 50 10 10 10 3; *gives all with E-6;
*%let parms=parms 50 10 10 10 10  10 10 10 .1/hold=9;
%let parms=parms 50 10 .1/hold=3;
%rely;

%let subset=if Side='Stroke' and Position='Finish' and Trial ne 5 and Trial ne 7 and
Trial ne 10;
%let title1=title1 "&dep; &subset; fixed serial";
%let convcrit=CONVH=1E-6 convf=1E-6;
*%let parms=parms 100 1 1 1 .01;
*%let parms=parms 20 10 10 10 10  1 1 1 .1/hold=9;
%let parms=parms 20 10 .1/hold=3;
%rely;

%let subset=if Side='Stroke' and Position='Arc' and Trial ne 5 and Trial ne 7 and Trial
ne 10;
%let title1=title1 "&dep; &subset; fixed serial";
%let convcrit=CONVH=1E-5 convf=1E-5;
*%let parms=parms 50 10 10 10 3;
*%let parms=parms 50 10 10 10 10  10 10 10 .1/hold=9;
%let parms=parms 50 10 .1/hold=3;
%rely;

*now run with bowside imported;

FILENAME REFFILE '/folders/myshortcuts/ExternalFiles/Projects/_VU
Melbourne/Ana Holt/S1P1 database_including oar angle data_for analysis.xlsx';

%let subset=if Side='Bow' and Position='Catch' and Trial ne 5 and Trial ne 10 and Trial
ne 7;
```

```
%let title1=title1 "&dep; &subset; fixed serial";
%let convcrit=CONVH=1E-6 convf=1E-6;
*%let parms=parms 50 10 10 10 3; *gives all with E-6;
*%let parms=parms 50 10 10 10 10  10 10 10 .1/hold=9;
%let parms=parms 50 10 .1/hold=3;
%rely;

%let subset=if Side='Bow' and Position='Finish' and Trial ne 5 and Trial ne 7 and Trial
ne 10;
%let title1=title1 "&dep; &subset; fixed serial";
%let convcrit=CONVH=1E-6 convf=1E-6;
*%let parms=parms 100 1 1 1 .01;
*%let parms=parms 20 10 10 10 10  1 1 1 .1/hold=9;
%let parms=parms 20 50 .1/hold=3;
%rely;

%let subset=if Side='Bow' and Position='Arc' and Trial ne 5 and Trial ne 7 and Trial ne
10;
%let title1=title1 "&dep; &subset; fixed serial";
%let convcrit=CONVH=1E-5 convf=1E-5;
*%let parms=parms 50 10 10 10 3;
*%let parms=parms 50 10 10 10 10  10 10 10 .1/hold=9;
%let parms=parms 50 10 .1/hold=3;
%rely;
/*
*now run with bowside imported;
*Trials 5 and 11 showed signs of slippage;
*now four units in the analysis;
FILENAME REFFILE '/folders/myshortcuts/ExternalFiles/Projects/_VU
Melbourne/Ana Holt/S1P1 database_including oar angle data_for analysis.xlsx';

%let subset=if Side='Bow' and Position='Catch' and Trial ne 5 and Trial ne 7 and Trial
ne 11; * and Trial ne 10;
%let title1=title1 "&dep; &subset; fixed serial";
%let convcrit=CONVH=1E-5 convf=1E-5;
*%let convcrit=CONVH=1E-7 convf=1E-7;
%let parms=parms 200 200 10 .01;
%let parms=parms 50 10 10 10 10 10 10 10 10 .1/hold=10;
%rely;

%let subset=if Side='Bow' and Position='Finish' and Trial ne 5 and Trial ne 7 and Trial
ne 11;
%let title1=title1 "&dep; &subset; fixed serial";
%let convcrit=CONVH=1E-5 convf=1E-5;
*%let convcrit=CONVH=1E-6 convf=1E-6;
%let parms=parms 20 10 10 10 10 1 1 1 1 .1/hold=10;
%rely;
```

```
%let subset=if Side='Bow' and Position='Arc' and Trial ne 5 and Trial ne 7 and Trial ne
11;
%let title1=title1 "&dep; &subset; fixed serial";
%let convcrit=CONVH=1E-5 convf=1E-5;
%let convcrit=CONVH=1E-6 convf=1E-6;
%let parms=parms 50 10 10 10 10 10 10 10 10 .1/hold=10;
%rely;
*/
```

Appendix R: Study Two statistical analysis SAS scripts for the analysis of means

```
%let logflag=1;
%let dep=PowerMean;
*%let magnithresh=-10; *smallest beneficial effect; *set lower down in program;
*if log transformation is used, express the above in percent units;
*beware: the between-study SD of the means for FAI is inflated by different methods;
*so 0.2x mean within-study SD is probably a better estimate of the smallest important;
%let dep1=5; *baseline values of the dependent in various study settings;
%let dep2=10;
%let dep3=20;
%let dep4=25; *choose other values for dep1-dep4, if you want to include dep4;
%let depPre2SD=230; *choose a round number close to 2 between-women SD of the
dependent;
*this is set lower down in the program;
*%let depPre2SD=200; *choose a round number close to 2 between-women SD of the
dependent;
*if log transformation is used, express the above in percent units;
%let decdep=1;
%let alpha=0.1;
%let delete=; *use this to delete any outliers;
%let nob=;
%let nob=nobound;
%let MagniThresh=1; *smallest beneficial % change in power;
%let deceff=1;
data _null_;
if &logflag then call symput('unitsrawlog',"percent");
else call symput('unitsrawlog',"raw");
data thresholds;
*set stdsd;
Units="Raw";
if &logflag then Units="%";
magnithresh=&MagniThresh;
if &logflag=0 then do; *these raw thresholds are actually via standardization;
Threshold="small   "; DeltaMeanBene=magnithresh; DeltaMeanHarm=-magnithresh;
SDthreshold=abs(magnithresh)/2; output;
  Threshold="moderate"; DeltaMeanBene=magnithresh*3; DeltaMeanHarm=-
magnithresh*3; SDthreshold=abs(DeltaMeanBene)/2; output;
  Threshold="large"; DeltaMeanBene=magnithresh*6; DeltaMeanHarm=-
magnithresh*6; SDthreshold=abs(DeltaMeanBene)/2; output;
  Threshold="vlarge"; DeltaMeanBene=magnithresh*10; DeltaMeanHarm=-
magnithresh*10; SDthreshold=abs(DeltaMeanBene)/2; output;
  Threshold="xlarge"; DeltaMeanBene=magnithresh*20; DeltaMeanHarm=-
magnithresh*20; SDthreshold=abs(DeltaMeanBene)/2; output;
  end;
else do;
  magnithresh=100*log(1+magnithresh/100);
```

```
  Threshold="small   "; DeltaMeanBene=100*exp(magnithresh/100)-100;
DeltaMeanHarm=100*exp(-magnithresh/100)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2)-100; output;
  Threshold="moderate"; DeltaMeanBene=100*exp(magnithresh/100*3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*3)-100; output;
  Threshold="large"; DeltaMeanBene=100*exp(magnithresh/100*1.6/0.3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*1.6/0.3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*1.6/0.3)-100; output;
  Threshold="vlarge"; DeltaMeanBene=100*exp(magnithresh/100*2.5/0.3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*2.5/0.3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*2.5/0.3)-100; output;
  Threshold="xlarge"; DeltaMeanBene=100*exp(magnithresh/100*4.0/0.3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*4.0/0.3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*4.0/0.3)-100; output;
  end;
title1 "&dep magnitude thresholds (&unitsrawlog), based on a given smallest important
for means of &magnithresh (&unitsrawlog).";
title2 "Thresholds for moderate, large, v.large and x.large are .9/.3x, 1.6/.3x, 2.5/.3x and
4/.3x the smallest important,";
title3 "i.e., competitive athlete thresholds; thresholds for SDs are half those for means.";
proc print noobs;
var Threshold Units DeltaMeanBene DeltaMeanHarm SDthreshold;
format DeltaMeanBene DeltaMeanHarm SDthreshold 5.&decdep;format
DeltaMeanBene DeltaMeanHarm SDthreshold 5.&decdep;
where &logflag=0;
run;
proc print noobs;
var Threshold Units DeltaMeanBene DeltaMeanHarm SDthreshold;
format DeltaMeanBene DeltaMeanHarm 5.&deceff SDthreshold 5.2;
where &logflag=1;
run;
*make macro variables for magnitude thresholds for the MBD steps;
data _null_;
length ThreshX $ 9;
set thresholds;
if &logflag then Thresh=abs(100*log(1+DeltaMeanBene/100)); *convert back to log
value, could do it with DeltaMeanHarm;
else Thresh=abs(DeltaMeanBene);
ThreshX=trim(Threshold)||'X';
call symput(ThreshX,Thresh);
run;
/*
data check;
Smallvalue=&smallx;
Modvalue=&moderatex;
proc print;run;
*/
```

```
*remove any sessions where InstrF did not work;
proc sort data=ss.meansd;
by SessionNo Stage;
data filter;
set ss.meansd;
keep SessionNo Stage NoOfMissing;
if Ergometer="InstrF" and NoNonMissing=0;
title "Sessions and stages with all values of InstrF missing";
title2 "Observations for all ergs in these stages NOT deleted";
proc print data=filter;
run; *14 stages, including all of Session 39;
data strokesinstrf;
set ss.meansd;
keep SessionNo Stage NoNonMissing;
if Ergometer="InstrF" and NoNonMissing>0;
rename NoNonMissing=StrokesInstrF;
title "Sessions and stages with InstrF showing at last 5 strokes more than an ergometer";
title2 "The observation for the ergometer in that stage is then deleted";
data check;
merge ss.meansd filter(in=a drop=NoOfMissing) strokesinstrf;
by SessionNo Stage;
*if a then delete;
LostStrokes=strokesinstrf-NoNonMissing;
if NoNonMissing>0 and LostStrokes>4;
keep SessionNo Stage Ergometer strokesinstrf NoNonMissing LostStrokes;
proc sort;
by Ergometer stage;
proc print;run;
data dat0;
merge ss.meansd filter(in=a drop=NoOfMissing) strokesinstrf;
by SessionNo Stage;
*if a then delete;
if NoNonMissing>0 and strokesinstrf-NoNonMissing>4 then delete;
run;
title "Numbers of observations (sessions) with non-missing data";
proc freq data=dat0;
tables Ergometer*Stage/norow nocol nopercent;
run;
title "Numbers of observations (sessions and stages) with non-missing data";
proc freq data=dat0;
tables ErgID*Ergometer/norow nocol nopercent;
run;
data dat1;
set dat0;
InvErr=1/(PowerSD/sqrt(NoNonMissing))**2; *quarter the number of non-missings;
*not used now;
*InvErr=1.5*1/(PowerSD/sqrt(NoNonMissing))**2; *increase sample size by factor of
1.5;
```

```
*InvErr=0.5*1/(PowerSD/sqrt(NoNonMissing))**2; *decrease sample size by factor of
0.5;
*the above made very little difference to anything;
if Ergometer ne "InstrC";
GateOar01=1; *dummy to suppress random effect for ErgID for C2 and InstrF;
if Ergometer="C2" or Ergometer="InstrF" then GateOar01=0;
NotInstrF=1;
if Ergometer="InstrF" then NotInstrF=0;
if SessionNo=8 and Stage=0 and Ergometer="Peach" then do;
  PowerMean=.; PowerSD=.;
  end;
*if ErgID ne 3203; *only one or two sessions for each stage; *keep it in now;
if Ergometer="Weba" and SessionNo=70 and Stage=0 then delete; *tValue=-7.4 in
mixed model;
Peach01=0; NK01=0; Weba01=0; C201=0;
if Ergometer="Peach" then Peach01=1;
if Ergometer="NK" then NK01=1;
if Ergometer="Weba" then Weba01=1;
if Ergometer="C2" then C201=1;
proc sort data=dat1;
by Stage;
run;
title "No of sessions per ergometer";
data temp;
set dat1;
if &dep ne .;
length ErgometerErgID $ 12;
ErgometerErgID=Ergometer||" "||left(trim(ErgID));
proc freq data=temp;
tables ErgometerErgID*Stage/norow nocol nopercent;
*by Ergometer;
run;
title "No of nonmissing strokes per session";
proc means data=temp maxdec=0;
var NoNonMissing;
class Stage ErgometerErgID;
where NoNonMissing>0;
run;
*remove and merge InstrF into the dataset;
proc sort data=dat1;
by Stage SessionNo;
data instrf;
set dat1;
if Ergometer="InstrF";
if &dep;
rename &dep=InstrF;
keep Stage SessionNo &dep;
data dat2;
```

```
merge dat1 instrf(in=a);
by Stage Sessionno;
if a;
if Ergometer ne "InstrF";
title "Bias in ergometers is evaluated at these means for InstrF (W).";
title2 "Evaluate proportional bias taking into account the between-session SD (%).";
proc means noprint data=instrf;
var InstrF;
by Stage;
output out=meaninstr mean= n=NoOfSessions std=SD;
data meaninstr1;
set meaninstr;
Instr=exp(InstrF/100);
SD=100*exp(SD/100)-100;
format InstrF SD 5.0;
proc print noobs;
var Stage NoOfSessions InstrF SD;
run;
proc standard data=dat2 mean=0 out=dat3;
var InstrF;
by Stage;
data clev est est1 est2 cov cov1 cov2 sumvar cov0 covr pred pred1 pred2 solf solr0 solr
solr1
 lsm lsm1 lsmdiff lsmdiff1 funnel funnel1 StudyIDres EstimateIDres;
ods select none;
title "&dep regression model with InstrF as predictor";
proc mixed covtest data=dat3 cl alpha=&alpha &nob CONVH=1E-5 convf=1E-5;
class Ergometer ErgID SessionNo Participant;
*weight InvErr;
model &dep=Ergometer Ergometer*InstrF/noint s cl ddfm=sat outp=pred outpm=predm
alpha=&alpha alphap=&alpha residual;
random int/subject=SessionNo s;
*random Peach01/s subject=Participant;
*random C201 Peach01 Weba01/s subject=Participant;
random int/s subject=Participant group=Ergometer;
random ErgID*GateOar01/group=Ergometer s;
*random ErgID*InstrF*GateOar01/group=Ergometer s; *ind diffs in prop bias, all
unclear;
*and consistent with 0 for Peach and Weba but ~0.5%/% for NK;
repeated/group=Ergometer;
parms 2  10 0 5 10  0 40 10 10  1 200 40 100;
*parms 0 40 10 10  0 0 0 0  1 200 40 100;
estimate "a.Mean bias C2" Ergometer 1 0 0 0/cl alpha=&alpha;
estimate "b.Mean bias NK" Ergometer 0 1 0 0/cl alpha=&alpha;
estimate "c.Mean bias Peach" Ergometer 0 0 1 0/cl alpha=&alpha;
estimate "d.Mean bias Weber" Ergometer 0 0 0 1/cl alpha=&alpha;
estimate "e.Mean bias Peach-C2" Ergometer -1 0 1 0/cl alpha=&alpha;
estimate "f.Mean bias NK-C2" Ergometer -1 1 0 0/cl alpha=&alpha;
```

```
estimate "g.Mean bias NK-Peach" Ergometer 0 1 -1 0/cl alpha=&alpha;
estimate "h.Mean bias Weba-C2" Ergometer -1 0 0 1/cl alpha=&alpha;
estimate "i.Prop. bias /1% C2" Ergometer*InstrF 1 0 0 0/cl alpha=&alpha;
estimate "j.Prop. bias /1% NK" Ergometer*InstrF 0 1 0 0/cl alpha=&alpha;
estimate "k.Prop. bias /1% Peach" Ergometer*InstrF 0 0 1 0/cl alpha=&alpha;
estimate "l.Prop. bias /1% Weber" Ergometer*InstrF 0 0 0 1/cl alpha=&alpha;
estimate "m.Prop. bias /10% C2" Ergometer*InstrF 9.5 0 0 0/cl alpha=&alpha;
estimate "n.Prop. bias /10% NK" Ergometer*InstrF 0 9.5 0 0/cl alpha=&alpha;
estimate "o.Prop. bias /10% Peach" Ergometer*InstrF 0 0 9.5 0/cl alpha=&alpha;
estimate "p.Prop. bias /10% Weber" Ergometer*InstrF 0 0 0 9.5/cl alpha=&alpha;
estimate "q.Prop. bias /40% C2" Ergometer*InstrF 33.6 0 0 0/cl alpha=&alpha;
estimate "r.Prop. bias /40% NK" Ergometer*InstrF 0 33.6 0 0/cl alpha=&alpha;
estimate "s.Prop. bias /40% Peach" Ergometer*InstrF 0 0 33.6 0/cl alpha=&alpha;
estimate "t.Prop. bias /40% Weber" Ergometer*InstrF 0 0 0 33.6/cl alpha=&alpha;
*lsmeans Ergometer/diff=control('InstrF') alpha=&alpha;
lsmeans Ergometer/cl alpha=&alpha;
ods output covparms=cov;
ods output lsmeans=lsm;
ods output diffs=lsmdiff;
ods output estimates=est;
ods output solutionr=solr;
*ods output solutionf=solf;
ods output classlevels=clev;
by Stage;
*where Ergometer ne "NK" and Ergometer ne "Weba";
run;
*ods listing;
ods select all;
title2 "Levels of nominal variables in the model";
proc print data=clev;
run;
title2 "Random effect variances, to check if model is working properly";
*title3 "Residual for InstrF should be 0.01";
proc print data=cov;run;
%let tvalue=4.0;
data pred1;
set pred;
if &logflag then do;
  &dep=exp(&dep/100);
  pred=exp(pred/100);
  end;
format StrokeRateMean 5.1;
if SessionNo=13 and Stage=5 then StrokeRateMean=.; *outlier;
proc sort;
by Ergometer Stage;
title2 "Residuals vs predicteds (back-transformed)";
ods graphics / reset width=14cm height=10cm imagemap attrpriority=none;
proc sgplot data=pred1; * uniform=Xscale;
```

```
styleattrs
  datacolors=(red orange yellow blue green purple cyan lightslategray black)
  datalinepatterns=(solid)
  datasymbols=(circlefilled squarefilled diamondfilled triangleleftfilled
TrianglerightFilled triangledownfilled
    plus x);
  *datacontrastcolors=(black); *red orange yellow blue green purple cyan lightslategray
black); *(red orange yellow blue green purple cyan white black);
scatter x=Pred y=Resid/markerattrs=(size=7) filledoutlinedmarkers
  MARKEROUTLINEATTRS=(color=black) group=Stage;
reg x=Pred Y=Resid/nomarkers lineattrs=(color=black) group=Stage;
*scatter x=pred y=Resid/markerattrs=(size=5 color=blue symbol=circlefilled)
filledoutlinedmarkers MARKERFILLATTRS=(color=black)
  group=PossessionType;
refline 0/axis=y lineattrs=(pattern=dot thickness=1 color=black);
by Ergometer;
where Ergometer ne "InstrF";
run;
ods graphics / reset;
title2 "Residuals vs StrokeRateMean";
ods graphics / reset width=14cm height=10cm imagemap attrpriority=none;
proc sgplot data=pred1; *uniform=all;
styleattrs
  datacolors=(red orange yellow blue green purple cyan white black)
  datalinepatterns=(solid)
  datasymbols=(circlefilled squarefilled diamondfilled triangleleftfilled
TrianglerightFilled triangledownfilled
    plus x);
*  datacontrastcolors=(red orange blue green purple);
scatter x=StrokeRateMean y=Resid/markerattrs=(size=7) filledoutlinedmarkers
  MARKEROUTLINEATTRS=(color=black) group=Stage;
reg x=StrokeRateMean Y=Resid/nomarkers lineattrs=(color=black) group=Stage;
*scatter x=pred y=Resid/markerattrs=(size=5 color=blue symbol=circlefilled)
filledoutlinedmarkers MARKERFILLATTRS=(color=black)
  group=PossessionType;
refline 0/axis=y lineattrs=(pattern=dot thickness=1 color=black);
by Ergometer;
where Ergometer ne "InstrF";
run;
ods graphics / reset;
proc print data=pred1;
var Ergometer--PowerSD &dep pred Studentresid;
title2 "Outliers (Standardized residual >&tvalue)";
title3 "Pred is the value of &dep predicted by the model";
format &dep pred resid 5.1 studentresid 5.1;
where  abs(StudentResid)>&tvalue;
run;
/*
```

```
proc print data=dat1;
where SessionNo=70 and Stage=0;
run;
*/
/*
*decode SessionNo;
proc sort data=dat1;
by SessionNo Participant Date Time;
run;
proc means noprint data=dat1;
by SessionNo Participant Date Time;
var &dep;
output out=decodesess(drop=_type_ _freq_ d) mean=d;
*proc print;run;
*decode SessionNo and ergs;
proc sort data=dat1;
by SessionNo Stage Ergometer ErgID;
run;
proc means noprint data=dat1;
by SessionNo Stage Ergometer ErgID;
var &dep;
output out=decodeerg(drop=_type_ _freq_ d) mean=d;
*proc print;run;
proc sort data=solr;
by SessionNo;
data solr1;
merge solr decodesess;
by SessionNo;
run;
title2 "Check random effect solution for outliers, where abs(tValue)>5";
title3 "Random-effect solution for Intercept";
title4 "which shows a couple of really weak and really strong rowers";
proc print data=solr1;
*where stage=0;
where effect="Intercept" and abs(tvalue)>5;
run;
*/
/*
data solr2;
set solr1;
*if Effect="Ergometer";
if Effect="NotInstrF";
proc sort data=solr2;
by SessionNo Stage Ergometer;
data solr3;
merge solr2(drop=ErgID) decodeerg;
by SessionNo Stage Ergometer;
drop StdErrPred DF Probt;
```

```
proc sort;
by Ergometer ErgID SessionNo Stage;
title2 "Check random effect solution for outliers, where abs(tValue)>5";
title3 "Random-effect solution for ergometer 'residual'";
*title4 "The solution for Intercept showed a couple of really weak and really strong
rowers";
proc print data=solr3;
var Effect  Ergometer   ErgID SessionNo Stage   Estimate    tValue  Participant Date
Time;
*where stage=0;
where abs(tvalue)>5;
by Ergometer;
run;
*/
/*
title2 "Fixed-effect coefficients";
proc print data=solf;run;
*title2 "Solution for random effects";
*proc print data=solr;run;
*/
/*
data covbtwn;
set cov;
SE2=stderr**2;
if covparm ne "Residual" and Group ne " Ergometer C2" and Group ne "Ergometer
InstrF";
proc means noprint;
var estimate se2;
output out=covbtwn1 sum=;
data covbtwn2;
covparm="Btwn settings";
set covbtwn1;
StdErr=sqrt(se2);
alpha=&alpha;
lower=estimate+probit(alpha/2)*StdErr;
upper=estimate-probit(alpha/2)*StdErr;
Zvalue=estimate/StdErr;
run;
data cov0;
set cov covbtwn2;
run;
*/
data cov1;
set cov;
*if covparm ne "Residual" and estimate ne 0; *Group ne "Ergometer C2" and Group ne
"Ergometer InstrF";
*if estimate ne 0; *Group ne "Ergometer C2" and Group ne "Ergometer InstrF";
if CovParm="GateOar01*ErgID" and Group="Ergometer C2" then delete;
```

```
DegFree=2*Zvalue**2;
a=1;b=1;c=1;
if covparm ne "Residual" then do; *for when allow only positive variance;
  Lower=estimate+probit(&alpha/2)*StdErr;
  Upper=estimate-probit(&alpha/2)*StdErr;
  end;
if estimate<0 then a=-1;
if lower<0 then b=-1;
if upper<0 then c=-1;
SD=a*sqrt(a*estimate);
lower=b*sqrt(b*lower);
upper=c*sqrt(c*upper);
MeanPlusSE=estimate+StdErr; *use this to get an approx. SE for the SD;
MeanMinusSE=estimate-StdErr;
ApproxSE=(sqrt(MeanPlusSE)-
sign(MeanMinusSE)*sqrt(sign(MeanMinusSE)*MeanMinusSE))/2;
array r SD lower upper ApproxSE;
if &logflag=1 then do over r;
  *r=exp(r/100);
  r=100*exp(r/100)-100;
  end;
*CLtd=sqrt(upper/lower);
CLpm=(upper-lower)/2;
Units="Raw";
if &logflag then Units="%";
Group=substr(Group,11);
proc sort;
by covparm group;
title2 "Random effects as SD (%) after adjustment for instrumentation power";
*title3 "Negative values (or zero if disallow negative) imply negative variance";
*title3 "ApproxSE is derived by back transformation of mean +/- SE for the variances";
title3 "GateOar01*ErgID is differences between ergometer units";
title4 "Intercept for SessionNo is potentially changes in instrumentation between
sessions";
title5 "Intercept for Participants is within-ergometer differences between participants";
title6 "Residual is within-ergometer within-participant session-to-session changes";
*title5 "Peach01 and Weba01 are participant differences";
proc print data=cov1 noobs;
var Stage covparm Group Subject Units SD CLpm lower upper alpha DegFree
ApproxSE;
format SD lower upper CLpm ApproxSE 5.1 DegFree 5.;
by covparm group;
*where covparm="Residual";
run;
/*
proc print data=cov1 noobs;
var Stage covparm Group Units SD CLpm lower upper alpha DegFree ApproxSE;
format SD lower upper CLpm ApproxSE 5.1 DegFree 5.;
```

```
by covparm group;
where covparm ne "Residual";
run;
*/
title2 "MBD for random effects";
data cov2;
set cov;
*if covparm ne "Residual" and Estimate ne 0; *Group ne "Ergometer C2" and Group ne
"Ergometer InstrF";
*if Estimate ne 0; *Group ne "Ergometer C2" and Group ne "Ergometer InstrF";
if CovParm="GateOar01*ErgID" and Group="Ergometer C2" then delete;
QualMag="Trivial ";
if sqrt(abs(estimate))>&smallx/2 then QualMag="Small";
if sqrt(abs(estimate))>&moderatex/2 then QualMag="Moderate";
if sqrt(abs(estimate))>&largex/2 then QualMag="Large";
if sqrt(abs(estimate))>&vlargex/2 then QualMag="Vlarge";
if sqrt(abs(estimate))>&xlargex/2 then QualMag="Xlarge";
DF=999;
MagniThresh=abs(&MagniThresh)/2;
if &logflag then Magnithresh=100*exp(abs(log(1+&magnithresh/100)/2))-100;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh)**2)/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh)**2)/StdErr,DF);
if &logflag then do;
  *if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-
(100*log(1+MagniThresh/100))**2)/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+(100*log(1+MagniThresh/100))**2)/StdErr,DF);
    end;
if covparm="Residual" then do;
  DF=2*Zvalue**2;
  ChancePos=100*probchi(DF*estimate/abs(MagniThresh)**2,DF);
  ChanceNeg=0;
  if &logflag then do;
    ChancePos=100*probchi(DF*estimate/(100*log(1+MagniThresh/100))**2,DF);
    ChanceNeg=0;
    end;
  end;
ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
ClinFlag=0; *want all inferences to be non-clinical for within-subject random effect;
*mechanistic inferences;
Precision="unclear";
Prob="        ";
Magni="     ";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then Precision="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then Precision="@99%  ";
```

```
if Precision ne "unclear" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if Precision ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
*end;
output;
data cov3;
set cov2;
a=1;b=1;c=1;
if covparm ne "Residual" then do; *for when allow only positive variance;
  Lower=estimate+probit(&alpha/2)*StdErr;
  Upper=estimate-probit(&alpha/2)*StdErr;
  end;
if estimate<0 then a=-1;
if lower<0 then b=-1;
if upper<0 then c=-1;
SD=a*sqrt(a*estimate);
lower=b*sqrt(b*lower);
upper=c*sqrt(c*upper);
DegFree=2*Zvalue**2;
array r SD lower upper;
if &logflag=1 then do over r;
  *r=exp(r/100);
  r=100*exp(r/100)-100;
  end;
*CLtd=sqrt(upper/lower);
CLpm=(upper-lower)/2;
Units="Raw";
if &logflag then Units="%";
*Magnithresh=1+Magnithresh/100;
Group=substr(Group,11);
run;
proc sort;
by covparm group;
title3 "Non-clinical inferences for SD representing random effects";
title4 "Magnithresh (%) is half the smallest difference for means (done via logs)";
title5 "GateOar01*ErgID is differences between ergometer units";
```

```
title6 "Intercept for SessionNo is potentially changes in instrumentation between
sessions";
title7 "Intercept for Participants is within-ergometer differences between participants";
title8 "Residual is within-ergometer within-participant session-to-session changes";
*title7 "Peach01 and Weba01 are participant differences";
*title8 "Intercept is differences between sessions";
proc print data=cov3 noobs;
*where clinflag=0;
var Stage covparm Group Subject Units SD CLpm lower upper alpha
  MagniThresh ChanceNeg ChanceTriv ChancePos QualMag Prob Magni Precision;
format SD CLpm lower upper MagniThresh 5.1 Probt best5. ChanceNeg ChanceTriv
  ChancePos 5.1 DegFree 5.0;
by covparm group;
*where covparm="Residual"; * and Group ne "InstrF" and covparm ne "Intercept";
run;
/*
proc print data=cov3 noobs;
*where clinflag=0;
var Stage covparm Group Units SD CLpm lower upper alpha
  MagniThresh ChanceNeg ChanceTriv ChancePos QualMag Prob Magni Precision;
format SD CLpm lower upper MagniThresh 5.1 Probt best5. ChanceNeg ChanceTriv
  ChancePos 5.1 DegFree 5.0;
by covparm group;
where covparm ne "Residual"; * and Group ne "InstrF" and covparm ne "Intercept";
run;
*/
title2 "Solution (%) for Ergometer ID to check consistency across stages";
title3 "Values are the ErgID's % above or below grand mean power for the ergometer";
title4 "Values shown are for stages with positive variance";
data solr3;
set solr;
if round(estimate,0.0000001) ne 0 and ErgID>0 and StdErrPred>0; *StdErrPred>0
deletes values when covparm is negative;
keep Stage Ergometer ErgID estimate;
Estimate=100*exp(estimate/100)-100;
format estimate 5.1;
proc sort;
by Ergometer ErgID Stage;
proc print noobs;
var Ergometer ErgID Stage Estimate;
by Ergometer ErgID;
run;
title2 "Mean InstrF and least-squares mean estimates of other ergs";
data lsm1;
length Ergometer $ 6;
set lsm meaninstr(in=b rename=(InstrF=Estimate));
if b then Ergometer="InstrF";
array a estimate lower upper;
```

```
do over a;
  a=exp(a/100);
  end;
CLpmApprox=(upper-lower)/2;
proc sort;
by Stage Ergometer;
proc print noobs;
var Stage Ergometer Estimate Lower Upper CLpmApprox Alpha;
format  Estimate Lower Upper CLpmApprox 5.&deceff alpha 5.2;
by Stage;
run;
data est1;
merge est meaninstr;
by Stage;
Units="%";
FirstLetter=substr(Label,1,1);
if FirstLetter="a" or FirstLetter="b" or FirstLetter="c" or FirstLetter="d" then do;
  Estimate=Estimate-InstrF;
  Lower=Lower-InstrF;
  Upper=Upper-InstrF;
  end;
*if &logflag then Units="factor";
array a estimate lower upper;
if &logflag and index(Label,"Prop. bias")=0 then do over a;
  a=100*exp(a/100)-100;
  end;
if &logflag and index(Label,"1%") then do over a;
  a=100*exp((a-1)/100)-100;
  end;
if &logflag and index(Label,"10%") then do over a;
  a=100*exp((a-9.5)/100)-100;
  end;
if &logflag and index(Label,"40%") then do over a;
  a=100*exp((a-33.6)/100)-100;
  end;
CLpmApprox=(Upper-Lower)/2;
run;
proc sort;
by Label Stage;
data est2;
set est1;
Label=substr(Label,3);
title2 "Differences in least-squares means";
proc print noobs data=est2;
var Label Stage Units Estimate CLpmApprox Lower Upper alpha StdErr DF;
format Estimate Lower Upper StdErr CLpmApprox 5.&deceff DF 5.0;
by notsorted Label;
where index(Label,"Prop. bias")=0;
```

```
run;
title2 "Proportional bias /1%";
proc print noobs data=est2;
var Label Stage Units Estimate CLpmApprox Lower Upper alpha StdErr DF;
format Estimate Lower Upper StdErr CLpmApprox 5.2 DF 5.0;
by notsorted Label;
where index(Label,"1%");
run;
title2 "Proportional bias /10%";
proc print noobs data=est2;
var Label Stage Units Estimate CLpmApprox Lower Upper alpha StdErr DF;
format Estimate Lower Upper StdErr CLpmApprox 5.1 DF 5.0;
by notsorted Label;
where index(Label,"10%");
run;
title2 "Proportional bias /40%";
proc print noobs data=est2;
var Label Stage Units Estimate CLpmApprox Lower Upper alpha StdErr DF;
format Estimate Lower Upper StdErr CLpmApprox 5.1 DF 5.0;
by notsorted Label;
where index(Label,"40%");
run;
*magnitude-based inferences for fixed effects;
*clin and non-clin MBDs are output and listed separately;
title2 "MBD for differences in least-squares means";
data est1;
merge est meaninstr;
by Stage;
Units="%";
FirstLetter=substr(Label,1,1);
if FirstLetter="a" or FirstLetter="b" or FirstLetter="c" or FirstLetter="d" then do;
  Estimate=Estimate-InstrF;
  Lower=Lower-InstrF;
  Upper=Upper-InstrF;
  end;
array a estimate lower upper;
if &logflag and index(Label,"10%") then do over a;
  a=a-9.5;
  end;
if &logflag and index(Label,"40%") then do over a;
  a=a-33.6;
  end;
length Prob $ 8 Magni $ 9 QualMag $ 8;
QualMag="Trivial";
if abs(estimate)>&smallx then QualMag="Small";
if abs(estimate)>&moderatex then QualMag="Moderate";
if abs(estimate)>&largex then QualMag="Large";
if abs(estimate)>&vlargex then QualMag="Vlarge";
```

```
if abs(estimate)>&xlargex then QualMag="Xlarge";
MagniThresh=&MagniThresh;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh))/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh))/StdErr,DF);
if &LogFlag=1 then do;
  if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  else do;
    ChancePos=100*(1-ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  end;
ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
ClinFlag=1; *want all inferences to be clinical initially;
*if index(label,"2SD") then ClinFlag=0; *covariates definitely need to be non-clinical;
*clinical inferences;
if clinflag then do;
ChPos=ChancePos; ChNeg=ChanceNeg;
if MagniThresh<0 then do;
  ChPos=ChanceNeg; ChNeg=ChancePos;
  end;
Prob=""; Magni=""; Precision="unclear";
if ChNeg<0.5 then do;
  Precision="@25/.5%";
  if ChNeg<0.1 then Precision="@5/.1% ";
  if ChanceTriv>25 then Magni="triv";
  if ChPos>25 then Magni="bene";
  Prob="possibly";
  if ChPos>75 or ChanceTriv>75 then Prob="likely  ";
  if ChPos>95 or ChanceTriv>95 then Prob="v.likely";
  if ChPos>99.5 or ChanceTriv>99.5 then Prob="m.likely";
  end;
else do; *i.e., ChNeg>0.5;
  if ChPos<25 then do;
    Precision="@25/.5%";
    if ChPos<5 then Precision="@5/.1% ";
    if ChanceTriv>25 then Magni="triv";
    if ChNeg>25 then Magni="harm";
    Prob="possibly";
    if ChNeg>75 or ChanceTriv>75 then Prob="likely  ";
    if ChNeg>95 or ChanceTriv>95 then Prob="v.likely";
    if ChNeg>99.5 or ChanceTriv>99.5 then Prob="m.likely";
    end;
  end;
```

```
if Precision="unclear" and
  (MagniThresh>0 and ORPosNeg>25/75/(0.5/99.5) or MagniThresh<0 and
ORNegPos>25/75/(0.5/99.5))
  then do;
  Precision="OR>66.3";
  Magni="bene";
  if ChPos>25 then Prob="possibly";
  if ChPos>75 then Prob="likely  ";
  if ChPos>95 then Prob="v.likely";
  if ChPos>99.5 then Prob="m.likely";
  end;
output;
end;
*mechanistic inferences;
ClinFlag=0;
Precision="unclear";
Prob="";
Magni="";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then Precision="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then Precision="@99%  ";
if Qualmag ne "Trivial" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  end;
if Precision ne "unclear" then do;
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if Precision ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
if 25<ChancePos<75 then xtra="/+ive";
if 25<ChanceNeg<75 then xtra="/-ive";
if Precision ne "unclear" and QualMag="Trivial" then Magni="triv"||xtra;
if Precision ne "unclear" and QualMag ne "Trivial" and prob="possibly" then do;
  if 25<ChanceTriv<75 then Magni=trim(Magni)||"/triv";
  end;
*end;
output;
proc sort;
by Label Stage;
```

```
data est2;
Units="Raw";
if &logflag then Units="%";
set est1;
if estimate=0 then do;
  estimate=.; magnithresh=.; magni=""; Precision=""; Prob=""; Units=""; QualMag="";
  end;
array a estimate lower upper;
if &logflag then do over a;
  a=100*exp(a/100)-100; *all are factors;
  end;
CLpmApprox=(Upper-lower)/2;
rename df=DegFree;
*Magnithresh=1+Magnithresh/100;
Label=substr(Label,3);
run;
*options ls=135 ps=80;
title3 "Non-clinical inferences";
title4 "Magnithresh is smallest mean change (%)";
proc print data=est2 noobs;
var Label Stage Units estimate CLpmApprox lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos QualMag Prob Magni Precision;
format estimate CLpmApprox lower upper MagniThresh 5.&decdep Probt best5.
ChanceNeg ChanceTriv
  ChancePos 5.1 DegFree 5.0;
by notsorted Label;
where clinflag=0 and index(Label,"Prop. bias")=0;
run;
*options ls=135 ps=80;
title2 "MBD for proportional bias /10%";
title3 "Non-clinical inferences";
title4 "Magnithresh is smallest mean change (%)";
proc print data=est2 noobs;
var Label Stage Units estimate CLpmApprox lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos QualMag Prob Magni Precision;
format estimate CLpmApprox lower upper MagniThresh 5.&decdep Probt best5.
ChanceNeg ChanceTriv
  ChancePos 5.1 DegFree 5.0;
by notsorted Label;
where clinflag=0 and index(Label,"10%");
run;
title2 "MBD for proportional bias /40%";
title3 "Non-clinical inferences";
title4 "Magnithresh is smallest mean change (%)";
proc print data=est2 noobs;
var Label Stage Units estimate CLpmApprox lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos QualMag Prob Magni Precision;
```

```
format estimate CLpmApprox lower upper MagniThresh 5.&decdep Probt best5.
ChanceNeg ChanceTriv
  ChancePos 5.1 DegFree 5.0;
by notsorted Label;
where clinflag=0 and index(Label,"40%");
run;
/*
data est4;
set est2;
if substr(Label,1,1)=".";
Label=substr(Label,2);
*options ls=145 ps=80;
title3 "Clinical inferences for mean effects in various settings, controlled for no
exercise";
title4 "Magnithresh is smallest beneficial change";
proc print data=est4 noobs;
where clinflag=1;
var label Units estimate CLpm lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos ORPosNeg ORNegPos Prob Magni
Precision;
format estimate CLpm lower upper MagniThresh 5.&decdep Probt best5. ORPosNeg
ORNegPos 5.0 ChanceNeg ChanceTriv
  ChancePos 5.1 DegFree 5.0;
run;
*/
*plot the metameans with the random-effect SD for the ErgIDs;
data covsd;
set cov1;
keep Stage Group SD;
*if Group ne "";
if covparm="GateOar01*ErgID";
rename Group=Ergometer;
proc sort;
by Stage Ergometer;
proc sort data=lsm1;
by Stage Ergometer;
data lsm2;
merge lsm1(keep=Stage Ergometer Estimate) covsd;
by Stage Ergometer;
if SD<0 then SD=.;
  MeanPlusSD=Estimate*(1+SD/100);
  MeanMinusSD=Estimate*(1-SD/100);
run;
*proc print data=lsm2;run;
*red orange yellowgreen blue mediumpurple;
title2 "Least-squares means and between-unit SDs";
ods graphics / reset width=18cm height=16cm imagemap attrpriority=none;
*proc sgplot data=mean&dep.1 noborder uniform=all;
```

```
*by Group;
*unstar the above two lines and star off the next to get separate graphs for animation;
proc sgplot data=lsm2 noborder;
styleattrs
  datacolors=(red orange blue green purple)
  datalinepatterns=(solid)
  datacontrastcolors=(red orange blue green purple)
  datasymbols=(circlefilled squarefilled diamondfilled triangleleftfilled x);
*TrianglerightFilled triangledownfilled;
*reg x=Rep y=Estimate /degree=1 nomarkers lineattrs=(thickness=1) group=Ergometer;
*scatter x=Rep y=Estimate /yerrorupper=MeanPlusSD yerrorlower=MeanMinusSD
  errorbarattrs=(color=black) groupdisplay=cluster clusterwidth=0.4 group=Ergometer
  filledoutlinedmarkers markerattrs=(size=18) name='abc';
*unstar the above two lines and star off the next two lines to fit regression polynomials;
scatter x=Stage y=Estimate /yerrorupper=MeanPlusSD yerrorlower=MeanMinusSD
  errorbarattrs=(color=black) ERRORCAPSCALE=0.8 groupdisplay=cluster
clusterwidth=0.4 group=Ergometer;
series x=Stage y=Estimate /markers filledoutlinedmarkers markerattrs=(size=12)
MARKEROUTLINEATTRS=(color=black)
  lineattrs=(pattern=solid) groupdisplay=cluster clusterwidth=0.4 group=Ergometer
name='abc';
keylegend 'abc' /title="Ergometer:" noborder titleattrs=(size=14) valueattrs=(size=14);
xaxis label="Stage" labelattrs=(size=14) valueattrs=(size=14)
  offsetmin=0.1 offsetmax=0.06 values=(0 to 7 by 1); * type=log logbase=2 minor;
yaxis label="&dep (W)" labelpos=top labelattrs=(size=14) valueattrs=(size=14) minor
minorcount=1 type=log logbase=2;
*refline 0;
run;
ods graphics / reset;
/*
*check within ergometer residuals vs stroke rate and power;
*merge solr with main data to get stroke rate and power;
data srandpower;
set pred;
keep Stage SessionNo Ergometer pred StrokeRateMean;
if SessionNo=13 and Stage=5 then StrokeRateMean=.; *outlier;
proc sort;
by Ergometer Stage SessionNo;
data solrx;
set solr;
*if effect="NotInstrF*Ergometer" and SessionNo>0 and Estimate ne 0;
if effect="NotInstrF" and SessionNo>0 and Estimate ne 0;
proc sort;
by Ergometer Stage SessionNo;
data solrx1;
merge solrx(in=a) srandpower;
by Ergometer Stage SessionNo;
if a;
```

```
*proc print;
run;
title2 "Ergometer residuals vs predicted PowerMean";
ods graphics / reset width=14cm height=10cm imagemap attrpriority=none;
proc sgplot data=solrx1 uniform=all;
styleattrs
  datacolors=(red orange yellow blue green purple cyan white black)
  datalinepatterns=(solid)
  datasymbols=(circlefilled squarefilled diamondfilled triangleleftfilled
TrianglerightFilled triangledownfilled
    plus x);
*  datacontrastcolors=(red orange blue green purple);
scatter x=Pred y=Estimate/markerattrs=(size=7) filledoutlinedmarkers
  MARKEROUTLINEATTRS=(color=black) group=Stage;
*scatter x=pred y=Resid/markerattrs=(size=5 color=blue symbol=circlefilled)
filledoutlinedmarkers MARKERFILLATTRS=(color=black)
  group=PossessionType;
*scatter x=StrokeNo y=Resid/markerattrs=(size=3 color=black symbol=circlefilled)
filledoutlinedmarkers MARKERFILLATTRS=(color=black);
refline 0/axis=y lineattrs=(pattern=dot thickness=1 color=black);
*by Ergometer;
by Ergometer Stage;
run;
ods graphics / reset;
title2 "Ergometer residuals vs StrokeRate";
ods graphics / reset width=14cm height=10cm imagemap attrpriority=none;
proc sgplot data=solrx1 uniform=all;
styleattrs
  datacolors=(red orange yellow blue green purple cyan white black)
  datalinepatterns=(solid)
  datasymbols=(circlefilled squarefilled diamondfilled triangleleftfilled
TrianglerightFilled triangledownfilled
    plus x);
*  datacontrastcolors=(red orange blue green purple);
scatter x=StrokeRateMean y=Estimate/markerattrs=(size=7) filledoutlinedmarkers
  MARKEROUTLINEATTRS=(color=black) group=Stage;
*scatter x=pred y=Resid/markerattrs=(size=5 color=blue symbol=circlefilled)
filledoutlinedmarkers MARKERFILLATTRS=(color=black)
  group=PossessionType;
*scatter x=StrokeNo y=Resid/markerattrs=(size=3 color=black symbol=circlefilled)
filledoutlinedmarkers MARKERFILLATTRS=(color=black);
refline 0/axis=y lineattrs=(pattern=dot thickness=1 color=black);
*by Ergometer;
by Ergometer Stage;
run;
ods graphics / reset;
*/
/*
```

```
*check for low stroke rate and for an apparent outlier for the Peach;
proc print data=ss.meansd;
*where StrokeRateMean<10;
where SessionNo=8 and Stage=0;
run;
*/
```

Appendix S: Study Two statistical analysis SAS scripts for the analysis of standard deviation

```
%let logflag=1;
%let dep=PowerMean;
*%let magnithresh=-10; *smallest beneficial effect; *set lower down in program;
*if log transformation is used, express the above in percent units;
*beware: the between-study SD of the means for FAI is inflated by different methods;
*so 0.2x mean within-study SD is probably a better estimate of the smallest important;
%let dep1=5; *baseline values of the dependent in various study settings;
%let dep2=10;
%let dep3=20;
%let dep4=25; *choose other values for dep1-dep4, if you want to include dep4;
%let depPre2SD=230; *choose a round number close to 2 between-women SD of the
dependent;
*this is set lower down in the program;
*%let depPre2SD=200; *choose a round number close to 2 between-women SD of the
dependent;
*if log transformation is used, express the above in percent units;
%let decdep=1;
%let alpha=0.1;
%let delete=; *use this to delete any outliers;
%let nob=;
%let nob=nobound;
%let MagniThresh=1; *smallest beneficial % change in power;
%let deceff=1;
data _null_;
if &logflag then call symput('unitsrawlog',"percent");
else call symput('unitsrawlog',"raw");
data thresholds;
*set stdsd;
Units="Raw";
if &logflag then Units="%";
magnithresh=&MagniThresh;
if &logflag=0 then do; *these raw thresholds are actually via standardization;
Threshold="small   "; DeltaMeanBene=magnithresh; DeltaMeanHarm=-magnithresh;
SDthreshold=abs(magnithresh)/2; output;
  Threshold="moderate"; DeltaMeanBene=magnithresh*3; DeltaMeanHarm=-
magnithresh*3; SDthreshold=abs(DeltaMeanBene)/2; output;
  Threshold="large"; DeltaMeanBene=magnithresh*6; DeltaMeanHarm=-
magnithresh*6; SDthreshold=abs(DeltaMeanBene)/2; output;
  Threshold="vlarge"; DeltaMeanBene=magnithresh*10; DeltaMeanHarm=-
magnithresh*10; SDthreshold=abs(DeltaMeanBene)/2; output;
  Threshold="xlarge"; DeltaMeanBene=magnithresh*20; DeltaMeanHarm=-
magnithresh*20; SDthreshold=abs(DeltaMeanBene)/2; output;
  end;
else do;
  magnithresh=100*log(1+magnithresh/100);
```

```
  Threshold="small   "; DeltaMeanBene=100*exp(magnithresh/100)-100;
DeltaMeanHarm=100*exp(-magnithresh/100)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2)-100; output;
  Threshold="moderate"; DeltaMeanBene=100*exp(magnithresh/100*3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*3)-100; output;
  Threshold="large"; DeltaMeanBene=100*exp(magnithresh/100*1.6/0.3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*1.6/0.3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*1.6/0.3)-100; output;
  Threshold="vlarge"; DeltaMeanBene=100*exp(magnithresh/100*2.5/0.3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*2.5/0.3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*2.5/0.3)-100; output;
  Threshold="xlarge"; DeltaMeanBene=100*exp(magnithresh/100*4.0/0.3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*4.0/0.3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*4.0/0.3)-100; output;
  end;
title1 "&dep magnitude thresholds (&unitsrawlog), based on a given smallest important
for means of &magnithresh (&unitsrawlog).";
title2 "Thresholds for moderate, large, v.large and x.large are .9/.3x, 1.6/.3x, 2.5/.3x and
4/.3x the smallest important,";
title3 "i.e., competitive athlete thresholds; thresholds for SDs are half those for means.";
proc print noobs;
var Threshold Units DeltaMeanBene DeltaMeanHarm SDthreshold;
format DeltaMeanBene DeltaMeanHarm SDthreshold 5.&decdep;format
DeltaMeanBene DeltaMeanHarm SDthreshold 5.&decdep;
where &logflag=0;
run;
proc print noobs;
var Threshold Units DeltaMeanBene DeltaMeanHarm SDthreshold;
format DeltaMeanBene DeltaMeanHarm 5.&deceff SDthreshold 5.2;
where &logflag=1;
run;
*make macro variables for magnitude thresholds for the MBD steps;
data _null_;
length ThreshX $ 9;
set thresholds;
if &logflag then Thresh=abs(100*log(1+DeltaMeanBene/100)); *convert back to log
value, could do it with DeltaMeanHarm;
else Thresh=abs(DeltaMeanBene);
ThreshX=trim(Threshold)||'X';
call symput(ThreshX,Thresh);
run;
/*
data check;
Smallvalue=&smallx;
Modvalue=&moderatex;
proc print;run;
*/
*remove any sessions where InstrF did not work;
proc sort data=ss.meansd;
```

```
by SessionNo Stage;
data filter;
set ss.meansd;
keep SessionNo Stage NoOfMissing;
if Ergometer="InstrF" and NoNonMissing=0;
title "Sessions and stages with all values of InstrF missing";
title2 "Observations for all ergs in these stages NOT deleted";
proc print data=filter;
run; *14 stages, including all of Session 39;
data strokesinstrf;
set ss.meansd;
keep SessionNo Stage NoNonMissing;
if Ergometer="InstrF" and NoNonMissing>0;
rename NoNonMissing=StrokesInstrF;
title "Sessions and stages with InstrF showing at last 5 strokes more than an ergometer";
title2 "The observation for the ergometer in that stage is then deleted";
data check;
merge ss.meansd filter(in=a drop=NoOfMissing) strokesinstrf;
by SessionNo Stage;
*if a then delete;
LostStrokes=strokesinstrf-NoNonMissing;
if NoNonMissing>0 and LostStrokes>4;
keep SessionNo Stage Ergometer strokesinstrf NoNonMissing LostStrokes;
proc sort;
by Ergometer stage;
proc print;run;
data dat0;
merge ss.meansd filter(in=a drop=NoOfMissing) strokesinstrf;
by SessionNo Stage;
*if a then delete;
if NoNonMissing>0 and strokesinstrf-NoNonMissing>4 then delete;
run;
title "Numbers of observations (sessions) with non-missing data";
proc freq data=dat0;
tables Ergometer*Stage/norow nocol nopercent;
run;
title "Numbers of observations (sessions and stages) with non-missing data";
proc freq data=dat0;
tables ErgID*Ergometer/norow nocol nopercent;
run;
data dat1;
set dat0;
InvErr=1/(PowerSD/sqrt(NoNonMissing))**2; *quarter the number of non-missings;
*not used now;
*InvErr=1.5*1/(PowerSD/sqrt(NoNonMissing))**2; *increase sample size by factor of
1.5;
*InvErr=0.5*1/(PowerSD/sqrt(NoNonMissing))**2; *decrease sample size by factor of
0.5;
*the above made very little difference to anything;
if Ergometer ne "InstrC";
```

```
GateOar01=1; *dummy to suppress random effect for ErgID for C2 and InstrF;
if Ergometer="C2" or Ergometer="InstrF" then GateOar01=0;
NotInstrF=1;
if Ergometer="InstrF" then NotInstrF=0;
if SessionNo=8 and Stage=0 and Ergometer="Peach" then do;
  PowerMean=.; PowerSD=.;
  end;
*if ErgID ne 3203; *only one or two sessions for each stage; *keep it in now;
if Ergometer="Weba" and SessionNo=70 and Stage=0 then delete; *tValue=-7.4 in
mixed model;
Peach01=0; NK01=0; Weba01=0; C201=0;
if Ergometer="Peach" then Peach01=1;
if Ergometer="NK" then NK01=1;
if Ergometer="Weba" then Weba01=1;
if Ergometer="C2" then C201=1;
proc sort data=dat1;
by Stage;
run;
title "No of sessions per ergometer";
data temp;
set dat1;
if &dep ne .;
length ErgometerErgID $ 12;
ErgometerErgID=Ergometer||" "||left(trim(ErgID));
proc freq data=temp;
tables ErgometerErgID*Stage/norow nocol nopercent;
*by Ergometer;
run;
title "No of nonmissing strokes per session";
proc means data=temp maxdec=0;
var NoNonMissing;
class Stage ErgometerErgID;
where NoNonMissing>0;
run;
*remove and merge InstrF into the dataset;
proc sort data=dat1;
by Stage SessionNo;
data instrf;
set dat1;
if Ergometer="InstrF";
if &dep;
rename &dep=InstrF;
keep Stage SessionNo &dep;
data dat2;
merge dat1 instrf(in=a);
by Stage Sessionno;
if a;
if Ergometer ne "InstrF";
title "Bias in ergometers is evaluated at these means for InstrF (W).";
title2 "Evaluate proportional bias taking into account the between-session SD (%).";
```

```
proc means noprint data=instrf;
var InstrF;
by Stage;
output out=meaninstr mean= n=NoOfSessions std=SD;
data meaninstr1;
set meaninstr;
InstrF=exp(InstrF/100);
SD=100*exp(SD/100)-100;
format InstrF SD 5.0;
proc print noobs;
var Stage NoOfSessions InstrF SD;
run;
proc standard data=dat2 mean=0 out=dat3;
var InstrF;
by Stage;
data clev est est1 est2 cov cov1 cov2 sumvar cov0 covr pred pred1 pred2 solf solr0 solr
solr1
 lsm lsm1 lsmdiff lsmdiff1 funnel funnel1 StudyIDres EstimateIDres;
ods select none;
title "&dep regression model with InstrF as predictor";
proc mixed covtest data=dat3 cl alpha=&alpha &nob CONVH=1E-5 convf=1E-5;
class Ergometer ErgID SessionNo Participant;
*weight InvErr;
model &dep=Ergometer Ergometer*InstrF/noint s cl ddfm=sat outp=pred outpm=predm
alpha=&alpha alphap=&alpha residual;
random int/subject=SessionNo s;
*random Peach01/s subject=Participant;
*random C201 Peach01 Weba01/s subject=Participant;
random int/s subject=Participant group=Ergometer;
random ErgID*GateOar01/group=Ergometer s;
*random ErgID*InstrF*GateOar01/group=Ergometer s; *ind diffs in prop bias, all
unclear;
*and consistent with 0 for Peach and Weba but ~0.5%/% for NK;
repeated/group=Ergometer;
parms 2  10 0 5 10  0 40 10 10  1 200 40 100;
*parms 0 40 10 10  0 0 0 0  1 200 40 100;
estimate "a.Mean bias C2" Ergometer 1 0 0 0/cl alpha=&alpha;
estimate "b.Mean bias NK" Ergometer 0 1 0 0/cl alpha=&alpha;
estimate "c.Mean bias Peach" Ergometer 0 0 1 0/cl alpha=&alpha;
estimate "d.Mean bias Weber" Ergometer 0 0 0 1/cl alpha=&alpha;
estimate "e.Mean bias Peach-C2" Ergometer -1 0 1 0/cl alpha=&alpha;
estimate "f.Mean bias NK-C2" Ergometer -1 1 0 0/cl alpha=&alpha;
estimate "g.Mean bias NK-Peach" Ergometer 0 1 -1 0/cl alpha=&alpha;
estimate "h.Mean bias Weba-C2" Ergometer -1 0 0 1/cl alpha=&alpha;
estimate "i.Prop. bias /1% C2" Ergometer*InstrF 1 0 0 0/cl alpha=&alpha;
estimate "j.Prop. bias /1% NK" Ergometer*InstrF 0 1 0 0/cl alpha=&alpha;
estimate "k.Prop. bias /1% Peach" Ergometer*InstrF 0 0 1 0/cl alpha=&alpha;
estimate "l.Prop. bias /1% Weber" Ergometer*InstrF 0 0 0 1/cl alpha=&alpha;
estimate "m.Prop. bias /10% C2" Ergometer*InstrF 9.5 0 0 0/cl alpha=&alpha;
estimate "n.Prop. bias /10% NK" Ergometer*InstrF 0 9.5 0 0/cl alpha=&alpha;
```

```
estimate "o.Prop. bias /10% Peach" Ergometer*InstrF 0 0 9.5 0/cl alpha=&alpha;
estimate "p.Prop. bias /10% Weber" Ergometer*InstrF 0 0 0 9.5/cl alpha=&alpha;
estimate "q.Prop. bias /40% C2" Ergometer*InstrF 33.6 0 0 0/cl alpha=&alpha;
estimate "r.Prop. bias /40% NK" Ergometer*InstrF 0 33.6 0 0/cl alpha=&alpha;
estimate "s.Prop. bias /40% Peach" Ergometer*InstrF 0 0 33.6 0/cl alpha=&alpha;
estimate "t.Prop. bias /40% Weber" Ergometer*InstrF 0 0 0 33.6/cl alpha=&alpha;
*lsmeans Ergometer/diff=control('InstrF') alpha=&alpha;
lsmeans Ergometer/cl alpha=&alpha;
ods output covparms=cov;
ods output lsmeans=lsm;
ods output diffs=lsmdiff;
ods output estimates=est;
ods output solutionr=solr;
*ods output solutionf=solf;
ods output classlevels=clev;
by Stage;
*where Ergometer ne "NK" and Ergometer ne "Weba";
run;
*ods listing;
ods select all;
title2 "Levels of nominal variables in the model";
proc print data=clev;
run;
title2 "Random effect variances, to check if model is working properly";
*title3 "Residual for InstrF should be 0.01";
proc print data=cov;run;
%let tvalue=4.0;
data pred1;
set pred;
if &logflag then do;
  &dep=exp(&dep/100);
  pred=exp(pred/100);
  end;
format StrokeRateMean 5.1;
if SessionNo=13 and Stage=5 then StrokeRateMean=.; *outlier;
proc sort;
by Ergometer Stage;
title2 "Residuals vs predicteds (back-transformed)";
ods graphics / reset width=14cm height=10cm imagemap attrpriority=none;
proc sgplot data=pred1; * uniform=Xscale;
styleattrs
  datacolors=(red orange yellow blue green purple cyan lightslategray black)
  datalinepatterns=(solid)
  datasymbols=(circlefilled squarefilled diamondfilled triangleleftfilled
TrianglerightFilled triangledownfilled
    plus x);
  *datacontrastcolors=(black); *red orange yellow blue green purple cyan lightslategray
black); *(red orange yellow blue green purple cyan white black);
scatter x=Pred y=Resid/markerattrs=(size=7) filledoutlinedmarkers
  MARKEROUTLINEATTRS=(color=black) group=Stage;
```

```
reg x=Pred Y=Resid/nomarkers lineattrs=(color=black) group=Stage;
*scatter x=pred y=Resid/markerattrs=(size=5 color=blue symbol=circlefilled)
filledoutlinedmarkers MARKERFILLATTRS=(color=black)
  group=PossessionType;
refline 0/axis=y lineattrs=(pattern=dot thickness=1 color=black);
by Ergometer;
where Ergometer ne "InstrF";
run;
ods graphics / reset;
title2 "Residuals vs StrokeRateMean";
ods graphics / reset width=14cm height=10cm imagemap attrpriority=none;
proc sgplot data=pred1; *uniform=all;
styleattrs
  datacolors=(red orange yellow blue green purple cyan white black)
  datalinepatterns=(solid)
  datasymbols=(circlefilled squarefilled diamondfilled triangleleftfilled
TrianglerightFilled triangledownfilled
    plus x);
*  datacontrastcolors=(red orange blue green purple);
scatter x=StrokeRateMean y=Resid/markerattrs=(size=7) filledoutlinedmarkers
  MARKEROUTLINEATTRS=(color=black) group=Stage;
reg x=StrokeRateMean Y=Resid/nomarkers lineattrs=(color=black) group=Stage;
*scatter x=pred y=Resid/markerattrs=(size=5 color=blue symbol=circlefilled)
filledoutlinedmarkers MARKERFILLATTRS=(color=black)
  group=PossessionType;
refline 0/axis=y lineattrs=(pattern=dot thickness=1 color=black);
by Ergometer;
where Ergometer ne "InstrF";
run;
ods graphics / reset;
proc print data=pred1;
var Ergometer--PowerSD &dep pred Studentresid;
title2 "Outliers (Standardized residual >&tvalue)";
title3 "Pred is the value of &dep predicted by the model";
format &dep pred resid 5.1 studentresid 5.1;
where  abs(StudentResid)>&tvalue;
run;
/*
proc print data=dat1;
where SessionNo=70 and Stage=0;
run;
*/
/*
*decode SessionNo;
proc sort data=dat1;
by SessionNo Participant Date Time;
run;
proc means noprint data=dat1;
by SessionNo Participant Date Time;
var &dep;
```

```
output out=decodesess(drop=_type_ _freq_ d) mean=d;
*proc print;run;
*decode SessionNo and ergs;
proc sort data=dat1;
by SessionNo Stage Ergometer ErgID;
run;
proc means noprint data=dat1;
by SessionNo Stage Ergometer ErgID;
var &dep;
output out=decodeerg(drop=_type_ _freq_ d) mean=d;
*proc print;run;
proc sort data=solr;
by SessionNo;
data solr1;
merge solr decodesess;
by SessionNo;
run;
title2 "Check random effect solution for outliers, where abs(tValue)>5";
title3 "Random-effect solution for Intercept";
title4 "which shows a couple of really weak and really strong rowers";
proc print data=solr1;
*where stage=0;
where effect="Intercept" and abs(tvalue)>5;
run;
*/
/*
data solr2;
set solr1;
*if Effect="Ergometer";
if Effect="NotInstrF";
proc sort data=solr2;
by SessionNo Stage Ergometer;
data solr3;
merge solr2(drop=ErgID) decodeerg;
by SessionNo Stage Ergometer;
drop StdErrPred DF Probt;
proc sort;
by Ergometer ErgID SessionNo Stage;
title2 "Check random effect solution for outliers, where abs(tValue)>5";
title3 "Random-effect solution for ergometer 'residual'";
*title4 "The solution for Intercept showed a couple of really weak and really strong
rowers";
proc print data=solr3;
var Effect  Ergometer   ErgID SessionNo Stage   Estimate    tValue  Participant Date
Time;
*where stage=0;
where abs(tvalue)>5;
by Ergometer;
run;
*/
```

```
/*
title2 "Fixed-effect coefficients";
proc print data=solf;run;
*title2 "Solution for random effects";
*proc print data=solr;run;
*/
/*
data covbtwn;
set cov;
SE2=stderr**2;
if covparm ne "Residual" and Group ne " Ergometer C2" and Group ne "Ergometer
InstrF";
proc means noprint;
var estimate se2;
output out=covbtwn1 sum=;
data covbtwn2;
covparm="Btwn settings";
set covbtwn1;
StdErr=sqrt(se2);
alpha=&alpha;
lower=estimate+probit(alpha/2)*StdErr;
upper=estimate-probit(alpha/2)*StdErr;
Zvalue=estimate/StdErr;
run;
data cov0;
set cov covbtwn2;
run;
*/
data cov1;
set cov;
*if covparm ne "Residual" and estimate ne 0; *Group ne "Ergometer C2" and Group ne
"Ergometer InstrF";
*if estimate ne 0; *Group ne "Ergometer C2" and Group ne "Ergometer InstrF";
if CovParm="GateOar01*ErgID" and Group="Ergometer C2" then delete;
DegFree=2*Zvalue**2;
a=1;b=1;c=1;
if covparm ne "Residual" then do; *for when allow only positive variance;
  Lower=estimate+probit(&alpha/2)*StdErr;
  Upper=estimate-probit(&alpha/2)*StdErr;
  end;
if estimate<0 then a=-1;
if lower<0 then b=-1;
if upper<0 then c=-1;
SD=a*sqrt(a*estimate);
lower=b*sqrt(b*lower);
upper=c*sqrt(c*upper);
MeanPlusSE=estimate+StdErr; *use this to get an approx. SE for the SD;
MeanMinusSE=estimate-StdErr;
ApproxSE=(sqrt(MeanPlusSE)-
sign(MeanMinusSE)*sqrt(sign(MeanMinusSE)*MeanMinusSE))/2;
```

```
array r SD lower upper ApproxSE;
if &logflag=1 then do over r;
  *r=exp(r/100);
  r=100*exp(r/100)-100;
  end;
*CLtd=sqrt(upper/lower);
CLpm=(upper-lower)/2;
Units="Raw";
if &logflag then Units="%";
Group=substr(Group,11);
proc sort;
by covparm group;
title2 "Random effects as SD (%) after adjustment for instrumentation power";
*title3 "Negative values (or zero if disallow negative) imply negative variance";
*title3 "ApproxSE is derived by back transformation of mean +/- SE for the variances";
title3 "GateOar01*ErgID is differences between ergometer units";
title4 "Intercept for SessionNo is potentially changes in instrumentation between
sessions";
title5 "Intercept for Participants is within-ergometer differences between participants";
title6 "Residual is within-ergometer within-participant session-to-session changes";
*title5 "Peach01 and Weba01 are participant differences";
proc print data=cov1 noobs;
var Stage covparm Group Subject Units SD CLpm lower upper alpha DegFree
ApproxSE;
format SD lower upper CLpm ApproxSE 5.1 DegFree 5.;
by covparm group;
*where covparm="Residual";
run;
/*
proc print data=cov1 noobs;
var Stage covparm Group Units SD CLpm lower upper alpha DegFree ApproxSE;
format SD lower upper CLpm ApproxSE 5.1 DegFree 5.;
by covparm group;
where covparm ne "Residual";
run;
*/
title2 "MBD for random effects";
data cov2;
set cov;
*if covparm ne "Residual" and Estimate ne 0; *Group ne "Ergometer C2" and Group ne
"Ergometer InstrF";
*if Estimate ne 0; *Group ne "Ergometer C2" and Group ne "Ergometer InstrF";
if CovParm="GateOar01*ErgID" and Group="Ergometer C2" then delete;
QualMag="Trivial ";
if sqrt(abs(estimate))>&smallx/2 then QualMag="Small";
if sqrt(abs(estimate))>&moderatex/2 then QualMag="Moderate";
if sqrt(abs(estimate))>&largex/2 then QualMag="Large";
if sqrt(abs(estimate))>&vlargex/2 then QualMag="Vlarge";
if sqrt(abs(estimate))>&xlargex/2 then QualMag="Xlarge";
DF=999;
```

```
MagniThresh=abs(&MagniThresh)/2;
if &logflag then Magnithresh=100*exp(abs(log(1+&magnithresh/100)/2))-100;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh)**2)/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh)**2)/StdErr,DF);
if &logflag then do;
  *if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-
(100*log(1+MagniThresh/100))**2)/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+(100*log(1+MagniThresh/100))**2)/StdErr,DF);
    end;
if covparm="Residual" then do;
  DF=2*Zvalue**2;
  ChancePos=100*probchi(DF*estimate/abs(MagniThresh)**2,DF);
  ChanceNeg=0;
  if &logflag then do;
    ChancePos=100*probchi(DF*estimate/(100*log(1+MagniThresh/100))**2,DF);
    ChanceNeg=0;
    end;
  end;
ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
ClinFlag=0; *want all inferences to be non-clinical for within-subject random effect;
*mechanistic inferences;
Precision="unclear";
Prob="        ";
Magni="     ";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then Precision="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then Precision="@99%  ";
if Precision ne "unclear" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if Precision ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
*end;
output;
data cov3;
set cov2;
a=1;b=1;c=1;
```

```
if covparm ne "Residual" then do; *for when allow only positive variance;
  Lower=estimate+probit(&alpha/2)*StdErr;
  Upper=estimate-probit(&alpha/2)*StdErr;
  end;
if estimate<0 then a=-1;
if lower<0 then b=-1;
if upper<0 then c=-1;
SD=a*sqrt(a*estimate);
lower=b*sqrt(b*lower);
upper=c*sqrt(c*upper);
DegFree=2*Zvalue**2;
array r SD lower upper;
if &logflag=1 then do over r;
  *r=exp(r/100);
  r=100*exp(r/100)-100;
  end;
*CLtd=sqrt(upper/lower);
CLpm=(upper-lower)/2;
Units="Raw";
if &logflag then Units="%";
*Magnithresh=1+Magnithresh/100;
Group=substr(Group,11);
run;
proc sort;
by covparm group;
title3 "Non-clinical inferences for SD representing random effects";
title4 "Magnithresh (%) is half the smallest difference for means (done via logs)";
title5 "GateOar01*ErgID is differences between ergometer units";
title6 "Intercept for SessionNo is potentially changes in instrumentation between
sessions";
title7 "Intercept for Participants is within-ergometer differences between participants";
title8 "Residual is within-ergometer within-participant session-to-session changes";
*title7 "Peach01 and Weba01 are participant differences";
*title8 "Intercept is differences between sessions";
proc print data=cov3 noobs;
*where clinflag=0;
var Stage covparm Group Subject Units SD CLpm lower upper alpha
  MagniThresh ChanceNeg ChanceTriv ChancePos QualMag Prob Magni Precision;
format SD CLpm lower upper MagniThresh 5.1 Probt best5. ChanceNeg ChanceTriv
  ChancePos 5.1 DegFree 5.0;
by covparm group;
*where covparm="Residual"; * and Group ne "InstrF" and covparm ne "Intercept";
run;
/*
proc print data=cov3 noobs;
*where clinflag=0;
var Stage covparm Group Units SD CLpm lower upper alpha
  MagniThresh ChanceNeg ChanceTriv ChancePos QualMag Prob Magni Precision;
format SD CLpm lower upper MagniThresh 5.1 Probt best5. ChanceNeg ChanceTriv
  ChancePos 5.1 DegFree 5.0;
```

```
by covparm group;
where covparm ne "Residual"; * and Group ne "InstrF" and covparm ne "Intercept";
run;
*/
title2 "Solution (%) for Ergometer ID to check consistency across stages";
title3 "Values are the ErgID's % above or below grand mean power for the ergometer";
title4 "Values shown are for stages with positive variance";
data solr3;
set solr;
if round(estimate,0.0000001) ne 0 and ErgID>0 and StdErrPred>0; *StdErrPred>0
deletes values when covparm is negative;
keep Stage Ergometer ErgID estimate;
Estimate=100*exp(estimate/100)-100;
format estimate 5.1;
proc sort;
by Ergometer ErgID Stage;
proc print noobs;
var Ergometer ErgID Stage Estimate;
by Ergometer ErgID;
run;
title2 "Mean InstrF and least-squares mean estimates of other ergs";
data lsm1;
length Ergometer $ 6;
set lsm meaninstr(in=b rename=(InstrF=Estimate));
if b then Ergometer="InstrF";
array a estimate lower upper;
do over a;
  a=exp(a/100);
  end;
CLpmApprox=(upper-lower)/2;
proc sort;
by Stage Ergometer;
proc print noobs;
var Stage Ergometer Estimate Lower Upper CLpmApprox Alpha;
format  Estimate Lower Upper CLpmApprox 5.&deceff alpha 5.2;
by Stage;
run;
data est1;
merge est meaninstr;
by Stage;
Units="%";
FirstLetter=substr(Label,1,1);
if FirstLetter="a" or FirstLetter="b" or FirstLetter="c" or FirstLetter="d" then do;
  Estimate=Estimate-InstrF;
  Lower=Lower-InstrF;
  Upper=Upper-InstrF;
  end;
*if &logflag then Units="factor";
array a estimate lower upper;
if &logflag and index(Label,"Prop. bias")=0 then do over a;
```

```
  a=100*exp(a/100)-100;
  end;
if &logflag and index(Label,"1%") then do over a;
  a=100*exp((a-1)/100)-100;
  end;
if &logflag and index(Label,"10%") then do over a;
  a=100*exp((a-9.5)/100)-100;
  end;
if &logflag and index(Label,"40%") then do over a;
  a=100*exp((a-33.6)/100)-100;
  end;
CLpmApprox=(Upper-Lower)/2;
run;
proc sort;
by Label Stage;
data est2;
set est1;
Label=substr(Label,3);
title2 "Differences in least-squares means";
proc print noobs data=est2;
var Label Stage Units Estimate CLpmApprox Lower Upper alpha StdErr DF;
format Estimate Lower Upper StdErr CLpmApprox 5.&deceff DF 5.0;
by notsorted Label;
where index(Label,"Prop. bias")=0;
run;
/*
title2 "Proportional bias /1%";
proc print noobs data=est2;
var Label Stage Units Estimate CLpmApprox Lower Upper alpha StdErr DF;
format Estimate Lower Upper StdErr CLpmApprox 5.2 DF 5.0;
by notsorted Label;
where index(Label,"1%");
run;
*/
title2 "Proportional bias /10%";
proc print noobs data=est2;
var Label Stage Units Estimate CLpmApprox Lower Upper alpha StdErr DF;
format Estimate Lower Upper StdErr CLpmApprox 5.1 DF 5.0;
by notsorted Label;
where index(Label,"10%");
run;
/*
title2 "Proportional bias /40%";
proc print noobs data=est2;
var Label Stage Units Estimate CLpmApprox Lower Upper alpha StdErr DF;
format Estimate Lower Upper StdErr CLpmApprox 5.1 DF 5.0;
by notsorted Label;
where index(Label,"40%");
run;
*/
```

```
*magnitude-based inferences for fixed effects;
*clin and non-clin MBDs are output and listed separately;
title2 "MBD for differences in least-squares means";
data est1;
merge est meaninstr;
by Stage;
Units="%";
FirstLetter=substr(Label,1,1);
if FirstLetter="a" or FirstLetter="b" or FirstLetter="c" or FirstLetter="d" then do;
  Estimate=Estimate-InstrF;
  Lower=Lower-InstrF;
  Upper=Upper-InstrF;
  end;
array a estimate lower upper;
if &logflag and index(Label,"10%") then do over a;
  a=a-9.5;
  end;
if &logflag and index(Label,"40%") then do over a;
  a=a-33.6;
  end;
length Prob $ 8 Magni $ 9 QualMag $ 8;
QualMag="Trivial";
if abs(estimate)>&smallx then QualMag="Small";
if abs(estimate)>&moderatex then QualMag="Moderate";
if abs(estimate)>&largex then QualMag="Large";
if abs(estimate)>&vlargex then QualMag="Vlarge";
if abs(estimate)>&xlargex then QualMag="Xlarge";
MagniThresh=&MagniThresh;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh))/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh))/StdErr,DF);
if &LogFlag=1 then do;
  if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  else do;
    ChancePos=100*(1-ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  end;
ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
ClinFlag=1; *want all inferences to be clinical initially;
*if index(label,"2SD") then ClinFlag=0; *covariates definitely need to be non-clinical;
*clinical inferences;
if clinflag then do;
ChPos=ChancePos; ChNeg=ChanceNeg;
if MagniThresh<0 then do;
  ChPos=ChanceNeg; ChNeg=ChancePos;
```

```
  end;
Prob=""; Magni=""; Precision="unclear";
if ChNeg<0.5 then do;
  Precision="@25/.5%";
  if ChNeg<0.1 then Precision="@5/.1% ";
  if ChanceTriv>25 then Magni="triv";
  if ChPos>25 then Magni="bene";
  Prob="possibly";
  if ChPos>75 or ChanceTriv>75 then Prob="likely  ";
  if ChPos>95 or ChanceTriv>95 then Prob="v.likely";
  if ChPos>99.5 or ChanceTriv>99.5 then Prob="m.likely";
  end;
else do; *i.e., ChNeg>0.5;
  if ChPos<25 then do;
    Precision="@25/.5%";
    if ChPos<5 then Precision="@5/.1% ";
    if ChanceTriv>25 then Magni="triv";
    if ChNeg>25 then Magni="harm";
    Prob="possibly";
    if ChNeg>75 or ChanceTriv>75 then Prob="likely  ";
    if ChNeg>95 or ChanceTriv>95 then Prob="v.likely";
    if ChNeg>99.5 or ChanceTriv>99.5 then Prob="m.likely";
    end;
  end;
if Precision="unclear" and
  (MagniThresh>0 and ORPosNeg>25/75/(0.5/99.5) or MagniThresh<0 and
ORNegPos>25/75/(0.5/99.5))
  then do;
  Precision="OR>66.3";
  Magni="bene";
  if ChPos>25 then Prob="possibly";
  if ChPos>75 then Prob="likely  ";
  if ChPos>95 then Prob="v.likely";
  if ChPos>99.5 then Prob="m.likely";
  end;
output;
end;
*mechanistic inferences;
ClinFlag=0;
Precision="unclear";
Prob="";
Magni="";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then Precision="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then Precision="@99%  ";
if Qualmag ne "Trivial" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  end;
if Precision ne "unclear" then do;
```

```
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if Precision ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
if 25<ChancePos<75 then xtra="/+ive";
if 25<ChanceNeg<75 then xtra="/-ive";
if Precision ne "unclear" and QualMag="Trivial" then Magni="triv"||xtra;
if Precision ne "unclear" and QualMag ne "Trivial" and prob="possibly" then do;
  if 25<ChanceTriv<75 then Magni=trim(Magni)||"/triv";
  end;
*end;
output;
proc sort;
by Label Stage;
data est2;
Units="Raw";
if &logflag then Units="%";
set est1;
if estimate=0 then do;
  estimate=.; magnithresh=.; magni=""; Precision=""; Prob=""; Units=""; QualMag="";
  end;
array a estimate lower upper;
if &logflag then do over a;
  a=100*exp(a/100)-100; *all are factors;
  end;
CLpmApprox=(Upper-lower)/2;
rename df=DegFree;
*Magnithresh=1+Magnithresh/100;
Label=substr(Label,3);
run;
*options ls=135 ps=80;
title3 "Non-clinical inferences";
title4 "Magnithresh is smallest mean change (%)";
proc print data=est2 noobs;
var Label Stage Units estimate CLpmApprox lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos QualMag Prob Magni Precision;
format estimate CLpmApprox lower upper MagniThresh 5.&decdep Probt best5.
ChanceNeg ChanceTriv
  ChancePos 5.1 DegFree 5.0;
by notsorted Label;
where clinflag=0 and index(Label,"Prop. bias")=0;
run;
```

```
*options ls=135 ps=80;
title2 "MBD for proportional bias /10%";
title3 "Non-clinical inferences";
title4 "Magnithresh is smallest mean change (%)";
proc print data=est2 noobs;
var Label Stage Units estimate CLpmApprox lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos QualMag Prob Magni Precision;
format estimate CLpmApprox lower upper MagniThresh 5.&decdep Probt best5.
ChanceNeg ChanceTriv
  ChancePos 5.1 DegFree 5.0;
by notsorted Label;
where clinflag=0 and index(Label,"10%");
run;
/*
title2 "MBD for proportional bias /40%";
title3 "Non-clinical inferences";
title4 "Magnithresh is smallest mean change (%)";
proc print data=est2 noobs;
var Label Stage Units estimate CLpmApprox lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos QualMag Prob Magni Precision;
format estimate CLpmApprox lower upper MagniThresh 5.&decdep Probt best5.
ChanceNeg ChanceTriv
  ChancePos 5.1 DegFree 5.0;
by notsorted Label;
where clinflag=0 and index(Label,"40%");
run;
*/
/*
data est4;
set est2;
if substr(Label,1,1)=".";
Label=substr(Label,2);
*options ls=145 ps=80;
title3 "Clinical inferences for mean effects in various settings, controlled for no
exercise";
title4 "Magnithresh is smallest beneficial change";
proc print data=est4 noobs;
where clinflag=1;
var label Units estimate CLpm lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos ORPosNeg ORNegPos Prob Magni
Precision;
format estimate CLpm lower upper MagniThresh 5.&decdep Probt best5. ORPosNeg
ORNegPos 5.0 ChanceNeg ChanceTriv
  ChancePos 5.1 DegFree 5.0;
run;
*/
*plot the metameans with the random-effect SD for the ErgIDs;
data covsd;
set cov1;
keep Stage Group SD;
```

```
*if Group ne "";
if covparm="GateOar01*ErgID";
rename Group=Ergometer;
proc sort;
by Stage Ergometer;
proc sort data=lsm1;
by Stage Ergometer;
data lsm2;
merge lsm1(keep=Stage Ergometer Estimate) covsd;
by Stage Ergometer;
if SD<0 then SD=.;
  MeanPlusSD=Estimate*(1+SD/100);
  MeanMinusSD=Estimate*(1-SD/100);
run;
title2 "Least-squares means and between-unit SDs";
proc print data=lsm2 noobs;run;
*red orange yellowgreen blue mediumpurple;
ods graphics / reset width=18cm height=16cm imagemap attrpriority=none;
*proc sgplot data=mean&dep.1 noborder uniform=all;
*by Group;
*unstar the above two lines and star off the next to get separate graphs for animation;
proc sgplot data=lsm2 noborder;
styleattrs
  datacolors=(red orange blue green purple)
  datalinepatterns=(solid)
  datacontrastcolors=(red orange blue green purple)
  datasymbols=(circlefilled squarefilled diamondfilled triangleleftfilled x);
*TrianglerightFilled triangledownfilled;
*reg x=Rep y=Estimate /degree=1 nomarkers lineattrs=(thickness=1) group=Ergometer;
*scatter x=Rep y=Estimate /yerrorupper=MeanPlusSD yerrorlower=MeanMinusSD
  errorbarattrs=(color=black) groupdisplay=cluster clusterwidth=0.4 group=Ergometer
  filledoutlinedmarkers markerattrs=(size=18) name='abc';
*unstar the above two lines and star off the next two lines to fit regression polynomials;
scatter x=Stage y=Estimate /yerrorupper=MeanPlusSD yerrorlower=MeanMinusSD
  errorbarattrs=(color=black) ERRORCAPSCALE=0.8 groupdisplay=cluster
clusterwidth=0.4 group=Ergometer;
series x=Stage y=Estimate /markers filledoutlinedmarkers markerattrs=(size=12)
MARKEROUTLINEATTRS=(color=black)
  lineattrs=(pattern=solid) groupdisplay=cluster clusterwidth=0.4 group=Ergometer
name='abc';
keylegend 'abc' /title="Ergometer:" noborder titleattrs=(size=14) valueattrs=(size=14);
xaxis label="Stage" labelattrs=(size=14) valueattrs=(size=14)
  offsetmin=0.1 offsetmax=0.06 values=(0 to 7 by 1); * type=log logbase=2 minor;
yaxis label="&dep (W)" labelpos=top labelattrs=(size=14) valueattrs=(size=14) minor
minorcount=1 type=log logbase=2;
*refline 0;
run;
ods graphics / reset;
/*
*check within ergometer residuals vs stroke rate and power;
```

```
*merge solr with main data to get stroke rate and power;
data srandpower;
set pred;
keep Stage SessionNo Ergometer pred StrokeRateMean;
if SessionNo=13 and Stage=5 then StrokeRateMean=.; *outlier;
proc sort;
by Ergometer Stage SessionNo;
data solrx;
set solr;
*if effect="NotInstrF*Ergometer" and SessionNo>0 and Estimate ne 0;
if effect="NotInstrF" and SessionNo>0 and Estimate ne 0;
proc sort;
by Ergometer Stage SessionNo;
data solrx1;
merge solrx(in=a) srandpower;
by Ergometer Stage SessionNo;
if a;
*proc print;
run;
title2 "Ergometer residuals vs predicted PowerMean";
ods graphics / reset width=14cm height=10cm imagemap attrpriority=none;
proc sgplot data=solrx1 uniform=all;
styleattrs
  datacolors=(red orange yellow blue green purple cyan white black)
  datalinepatterns=(solid)
  datasymbols=(circlefilled squarefilled diamondfilled triangleleftfilled
TrianglerightFilled triangledownfilled
    plus x);
*  datacontrastcolors=(red orange blue green purple);
scatter x=Pred y=Estimate/markerattrs=(size=7) filledoutlinedmarkers
  MARKEROUTLINEATTRS=(color=black) group=Stage;
*scatter x=pred y=Resid/markerattrs=(size=5 color=blue symbol=circlefilled)
filledoutlinedmarkers MARKERFILLATTRS=(color=black)
  group=PossessionType;
*scatter x=StrokeNo y=Resid/markerattrs=(size=3 color=black symbol=circlefilled)
filledoutlinedmarkers MARKERFILLATTRS=(color=black);
refline 0/axis=y lineattrs=(pattern=dot thickness=1 color=black);
*by Ergometer;
by Ergometer Stage;
run;
ods graphics / reset;
title2 "Ergometer residuals vs StrokeRate";
ods graphics / reset width=14cm height=10cm imagemap attrpriority=none;
proc sgplot data=solrx1 uniform=all;
styleattrs
  datacolors=(red orange yellow blue green purple cyan white black)
  datalinepatterns=(solid)
  datasymbols=(circlefilled squarefilled diamondfilled triangleleftfilled
TrianglerightFilled triangledownfilled
    plus x);
```

```
*  datacontrastcolors=(red orange blue green purple);
scatter x=StrokeRateMean y=Estimate/markerattrs=(size=7) filledoutlinedmarkers
  MARKEROUTLINEATTRS=(color=black) group=Stage;
*scatter x=pred y=Resid/markerattrs=(size=5 color=blue symbol=circlefilled)
filledoutlinedmarkers MARKERFILLATTRS=(color=black)
  group=PossessionType;
*scatter x=StrokeNo y=Resid/markerattrs=(size=3 color=black symbol=circlefilled)
filledoutlinedmarkers MARKERFILLATTRS=(color=black);
refline 0/axis=y lineattrs=(pattern=dot thickness=1 color=black);
*by Ergometer;
by Ergometer Stage;
run;
ods graphics / reset;
*/
/*
*check for low stroke rate and for an apparent outlier for the Peach;
proc print data=ss.meansd;
*where StrokeRateMean<10;
where SessionNo=8 and Stage=0;
run;
*/
```

Appendix T: Study Three statistical analysis SAS script for general linear mixed modelling of stroke data (initial analyses)

```
/*
This creates ss.racepower as follows:
reads Complete_S6_Database_V2 ex Ana attachment.xlsx to get PowerTotal
PowerStroke PowerBow StrokeTime
reads S3 Race Times_updated.xlsx to get RaceTime BoatPower MeanStrokePower
MeanBowPower
checks agreement of StrokeTime with RaceTime and
  PowerTotal PowerStroke PowerBow with BoatPower MeanStrokePower
MeanBowPower
uses ss.study3forMulti with code from predict speed with power inddiffs no pred
2June20.sas to get and merge in
  random-effect solution for BoatID (BoatEfficiency) and StrokeSet (Environment) and
the residuals
renames MeanStrokePower MeanBowPower as StrokePower BowPower (but probably
not to be used)
Here are the variables in ss.racepower:
  BoatClass Gender BoatID Event Race NoOfStrokes StrokeTime Category RaceTime
RaceOrder Year
  BoatPower StrokePower BowPower BoatEfficiency StrokeSet Date Time
Environment Variability
  BoatEffSD EnvironSD
BoatEfficiency, Environment, Variability, BoatEffSD and EnvironSD are log
transformed already.
Use this dataset with a modified version of predict speed with power boatpred
23Apr20.sas
*/
*read in updated data but not to be used for previous analyses?;
libname ss '/folders/myshortcuts/ExternalFiles/Projects/_VU Melbourne/Ana
Holt/Study 3';
*FILENAME REFFILE '/folders/myshortcuts/ExternalFiles/Projects/_VU
Melbourne/Ana Holt/Study 3/S3 Compiled Dataset_2020.05.22.xlsx';
*FILENAME REFFILE '/folders/myshortcuts/ExternalFiles/Projects/_VU
Melbourne/Ana Holt/Study 3/Complete_S6_Database_V2 1Oct20.xlsx';
FILENAME REFFILE '/folders/myshortcuts/ExternalFiles/Projects/_VU
Melbourne/Ana Holt/Study 3/Complete_S6_Database_V2 ex Ana attachment.xlsx';

PROC IMPORT DATAFILE=REFFILE
	DBMS=XLSX
	OUT=dat0 replace;
	GETNAMES=YES;
RUN;

data dat1;
set dat0;
drop Jerk--RowNumber;
*drop LoganVer SplitName StrokeNoChange StrokesTaken Split_Distance Precipation
RaceDirectionBoatCalc
```

```
  TransPowerHandle phtDrive PowerHandleTot WorkHandle PowerHandle
PowerHandleDrive;
*if StrokesTaken=1;
attrib _character_ _numeric_ label="";
if Event ne "NSWSC20";
if BoatID="VBCaVMHM2-" and Race="Heat" then delete;
if BoatID="VRMLM1x" and Race="Final" then delete;
if BoatID="WHHM1x" and Race="Heat" then delete; *missing too many strokes;
if BoatID="VKGVJHW2-" and Race="Rep" then delete; *ditto;
if BoatID="AHGM1x" and Race="Final" then delete;
if BoatID="VCWW1x" and Race="Semi" then delete;
run;

*proc freq data=ss.study3;
*tables race*event/nocol norow nopercent;
run;

proc sort data=dat1;
by BoatClass Gender BoatID Event Race Stroke;

proc means noprint data=dat1;
var PhaseLength PowerTotal PowerStroke PowerBow;
output out=dat1a(drop=PhaseLength _type_ _freq_) mean= sum=StrokeTime;
by BoatClass Gender BoatID Event Race Stroke;

data dat1b;
set dat1a;
array a PowerTotal PowerStroke PowerBow;
do over a;
  a=a*StrokeTime;
  end;

proc means noprint data=dat1b;
var PowerTotal PowerStroke PowerBow StrokeTime;
output out=dat1c(drop=_type_ rename=(_freq_=NoOfStrokes)) sum=;
by BoatClass Gender BoatID Event Race;

data dat1d;
set dat1c;
array a PowerTotal PowerStroke PowerBow;
do over a;
  a=a/StrokeTime;
  end;
StrokeRate=NoOfStrokes/StrokeTime*60;
format StrokeRate 5.1 PowerTotal PowerStroke PowerBow 5.0 StrokeTime mmss6.0;

*proc print data=dat1d(obs=10);run;

*read in and merge racetimes;
```

```
FILENAME REFFILE '/folders/myshortcuts/ExternalFiles/Projects/_VU
Melbourne/Ana Holt/Study 3/S3 Race Times_updated.xlsx';

PROC IMPORT DATAFILE=REFFILE
	DBMS=XLSX
	OUT=racetimes replace;
	GETNAMES=YES;
	attrib _character_ _numeric_ label="";
RUN;
*proc print data=racetimes(obs=100);
run;

*RaceTime is in seconds formatted min:s.0;
*proc print data=racetimes(obs=10);
*format racetime 5.1; run;

proc sort data=racetimes;
by Event BoatID Race; *not got gender and boatclass in this dataset;

data racetimes1;
set racetimes;
if Event ne "NSWSC20";
if BoatID="VBCaVMHM2-" and Race="Heat" then delete;
if BoatID="VRMLM1x" and Race="Final" then delete;
if BoatID="WHHM1x" and Race="Heat" then delete; *missing too many strokes;
if BoatID="VKGVJHW2-" and Race="Rep" then delete; *ditto;
if BoatID="AHGM1x" and Race="Final" then delete;
if BoatID="VCWW1x" and Race="Semi" then delete; *this one missed off previously;

proc sort data=dat1d;
by Event BoatID Race;

/*
data check;
merge dat1d(in=a) racetimes1(in=b);
by Event BoatID Race;
if b and not a;
*if a and not b;
*if a;
run;

title "Data in racetimes file but not in Complete_S6_Database_V2";
proc print;run;

data check;
merge dat1d(in=a) racetimes1(in=b);
by Event BoatID Race;
*if b and not a;
if a and not b;
*if a;
```

```
title "Data in Complete_S6_Database_V2 but not in racetimes file";
proc print;run;
*/
data power;
merge dat1d(in=a) racetimes1(in=b);
by Event BoatID Race;
if b;
TimeDiffPC=100*StrokeTime/RaceTime-100;
PowerDiffPC=100*PowerTotal/BoatPower-100;
BowPowerDiffPC=100*PowerBow/MeanBowPower-100;
StrokePowerDiffPC=100*PowerStroke/MeanStrokePower-100;
format TimeDiffPC PowerDiffPC 5.1;
if abs(TimeDiffPC)>3 then TimeMarker="***  ";
if abs(TimeDiffPC)>5 then TimeMarker="*****";
if abs(PowerDiffPC)>3 or abs(BowPowerDiffPC)>3 or abs(StrokePowerDiffPC)>3
then PowerMarker="***  ";
if abs(PowerDiffPC)>5 or abs(BowPowerDiffPC)>5 or abs(StrokePowerDiffPC)>5
then PowerMarker="*****";
format TimeDiffPC PowerDiffPC BowPowerDiffPC StrokePowerDiffPC 5.1;
run;

proc sort;
by BoatClass Gender;

options ls=80 ps=40;
title "StrokeTime in S6 database (Y axis) vs RaceTime in race times database (X axis)";
proc plot;
plot StrokeTime*RaceTime;
by BoatClass Gender;
run;

title "Power in S6 database (Y axis) vs power in race times database (X axis)";
proc plot;
plot PowerTotal*BoatPower;
by BoatClass Gender;
run;

title2 "*** and ***** indicate >3% and >5% difference in time and power";
proc print;
by BoatClass Gender;
run;

data power1;
set power;
keep BoatClass Gender BoatID Event Race NoOfStrokes StrokeRate BoatPower
MeanBowPower MeanStrokePower StrokeTime Category
  RaceTime RaceOrder Year;
rename MeanBowPower=BowPower MeanStrokePower=StrokePower;
```

```
*keep BoatClass Gender BoatID Event Race NoOfStrokes PowerTotal PowerStroke
PowerBow StrokeTime Category
  RaceTime RaceOrder Year;
*these are from the S6 database, plus official RaceTime;
run;

*what follows is predict speed with power inddiffs no pred 2June20.sas;
libname ss '/folders/myshortcuts/ExternalFiles/Projects/_VU Melbourne/Ana
Holt/Study 3';

*VBCaM2-     VBCaVMHM2-         M        2-        Heat;

data dat1;
set ss.study3forMulti;
attrib _character_ _numeric_ label="";
run;

*proc print data=ss.study3forMulti(obs=100);
run;
%let dep=AvBoatVel;
%let predboat=;
%let decpredboat=2;
/*
%let predboat=RecovAccelPeak;
%let decpredboat=2;

%let predboat=StrokeRate;
%let decpredboat=1;

%let predboat=DriveAccelMax;
%let decpredboat=2;

%let predboat=DriveAccelMin;
%let decpredboat=2;
*/
%let logflag=1;
%let logflagpred=0;

%let alpha=0.1;
%let decdep=1;
%let deceff=1;
%let nob=;
%let convcrit=CONVH=1E-8 convf=1E-8;
%let StdzedMagniThresh=0.20; *smallest stdized beneficial change;
%let MagniThresh=0.3; *smallest beneficial change;
%let parms=;

%let subset=if StrokeNo>10;
%let title1=title1 "&dep predicted by PowerPeach and StrokeRate in a log-log mixed
model";
```

```
data _null_;
if &logflag then call symput('unitsrawlog',"percent");
else call symput('unitsrawlog',"raw");
run;

/*
proc sort data=dat1;
by Gender Participant Race;

ods graphics / reset width=20cm height=16cm imagemap attrpriority=none;
title "Scatterplot of &dep vs StrokeNo";
proc sgplot data=dat1 uniform=scale;
styleattrs
  datacolors=(black blue red pink greenyellow)
  datalinepatterns=(dot)
  datacontrastcolors=(black blue red pink greenyellow)
  datasymbols=(circlefilled);
  *datasymbols=(circlefilled squarefilled diamondfilled trianglefilled);
*reg x=Vicon y=&dep/nomarkers name='def' group=DeviceUnit;
*reg x=Vicon1 y=Identity/nomarkers name='def' lineattrs=(color=black pattern=dash
thickness=0.5);
scatter x=StrokeNo y=&dep/markerattrs=(size=5) filledoutlinedmarkers name='abc'
group=Race;
*scatter x=StrokeNo y=&dep/groupdisplay=cluster clusterwidth=0.3
markerattrs=(size=8) filledoutlinedmarkers group=DeviceUnit  name='abc';
*series x=&dep y=MeanLine /lineattrs=(pattern=dash thickness=1 color=black);
*keylegend 'def' /noborder titleattrs=(size=16) valueattrs=(size=16);
keylegend 'abc' /title="Race:" noborder titleattrs=(size=16) valueattrs=(size=16);
yaxis label="&dep" labelpos=top labelattrs=(size=16) valueattrs=(size=16);
xaxis label="StrokeNo" labelattrs=(size=16) valueattrs=(size=16);
refline 10/axis=x lineattrs=(pattern=dot thickness=1 color=black);
*refline MeanDep/axis=x lineattrs=(pattern=dash thickness=0.25 color=black);
by Gender Participant;
*where Participant="VMTW2-";
where StrokeNo>3; * and  Participant="VMTW2-";
run;
ods graphics/reset;
*/
proc sort data=dat1;
by Date Time BoatID ;

data dat2;
retain StrokeSet 0;
set dat1;
if lag(Date) ne Date or lag(Time) ne Time or lag(BoatID) ne BoatID then
StrokeSet=StrokeSet+1;
*&subset;
/*
if &logflag=1 then &dep=100*log(&dep);
```

```
if &logflagpred=1 then &pred=100*log(&pred);
*/
if Event ne "NSWSC20";
if BoatID="VBCaVMHM2-" and Race="Heat" then delete;
if BoatID="VRMLM1x" and Race="Final" then delete;
if BoatID="WHHM1x" and Race="Heat" then delete; *missing too many strokes;
if BoatID="VKGVJHW2-" and Race="Rep" then delete; *ditto;
if BoatID="AHGM1x" and Race="Final" then delete;
if BoatID="VCWW1x" and Race="Semi" then delete;
if Event="Underage" then Event="Trials";
run;

proc sort data=dat2;
by BoatClass Gender BoatID StrokeSet StrokeNo;
run;

data bow;
set dat2;
if Side="B";
keep Event Time &predboat StrokeRate BoatClass Gender Race BoatID Date
Participant StrokeSet StrokeNo StrokeTime PowerPeach AvBoatVel CatchSlipPeach;
rename Time=TimeB Participant=RowerBow PowerPeach=PowerPeachBow
CatchSlipPeach=CatchSlipBow;
&subset;

data stroke;
set dat2;
if Side="S";
keep Event Time BoatClass Gender Race BoatID Participant StrokeSet StrokeNo
PowerPeach CatchSlipPeach WindDirectionDec WindAve;
rename Time=TimeS Participant=RowerStroke PowerPeach=PowerPeachStroke
CatchSlipPeach=CatchSlipStroke;
&subset;

data dat4;
merge bow(in=a) stroke(in=b);
by BoatClass Gender BoatID StrokeSet StrokeNo;
if a and not b or b and not a then delete; *only 10 obs, plus VRMLM1x for one race;
PowerPeach=PowerPeachBow+PowerPeachStroke;
Time=TimeB;
if TimeB="" then Time=TimeS;
drop TimeB TimeS;
*if Race="Trials" then Race="Final";
*if Race="Rep" or Race="Semi" then Race="Heat";
*if BoatID="AHHLM1x" or  BoatID="ANKLM1x" or  BoatID="SOMLM1x" or
BoatID="VACM1x" or  BoatID="VENM1x";
*if Gender="W" and BoatClass="2-";

data decodeset;
set dat4;
```

```
if lag(StrokeSet) ne StrokeSet;
keep BoatClass Gender StrokeSet Date Time Race BoatID Event;
run;

*proc print data=bow(obs=100);run;
/*
proc sort data=dat1;
by BoatClass Gender Participant Side;

data decodeside;
set dat1;
if lag(BoatID) ne BoatID or lag(Side) ne Side;
keep BoatClass Gender BoatID Side Participant;

*proc print noobs;
run;
*/

title "Within-boat simple stats for AvBoatVel (m/s)";
title2 "Nobs is the number of stroke sets";
proc means noprint data=dat4;
var AvBoatVel;
by BoatClass Gender BoatID StrokeSet;
*where Side="B";
output out=meansd mean=WthnBoatMean std=WthnBoatSD;

proc means maxdec=2;
var WthnBoatMean WthnBoatSD;
class BoatClass Gender;
run;


title "Within-boat simple stats for PowerPeach (W)";
title2 "Nobs is the number of stroke sets";
proc means noprint data=dat4;
var PowerPeach;
by BoatClass Gender BoatID StrokeSet;
*where Side="B";
output out=meansd mean=WthnBoatMean std=WthnBoatSD;

proc means maxdec=0;
var WthnBoatMean WthnBoatSD;
class BoatClass Gender;
run;

title "Within-boat simple stats for StrokeRate (spm)";
title2 "Nobs is the number of stroke sets";
proc means noprint data=dat4;
var StrokeRate;
by BoatClass Gender BoatID StrokeSet;
```

```
*where Side="B";
output out=meansd mean=WthnBoatMean std=WthnBoatSD;

proc means maxdec=1;
var WthnBoatMean WthnBoatSD;
class BoatClass Gender;
run;

data dat5;
set dat4;
PowerCubRoot=PowerPeach**(1/3);
if &logflag then do;
  &dep=100*log(&dep);
  PowerPeach=100*log(PowerPeach);
  PowerCubRoot=100*log(PowerCubRoot);
  StrokeRate=100*log(StrokeRate);
  end;
run;

*proc print data=dat3(obs=1000);
run;

title "Within-boat simple stats for log-transformed AvBoatVel";
title2 "Nobs is the number of stroke sets";
proc means noprint data=dat5;
var AvBoatVel;
by BoatClass Gender BoatID StrokeSet;
*where Side="B";
output out=meansd mean=WthnBoatMean std=WthnBoatSD;

proc means maxdec=1;
var WthnBoatMean WthnBoatSD;
class BoatClass Gender;
run;

title "Within-boat simple stats for log-transformed PowerPeach";
title2 "Nobs is the number of stroke sets";
proc means noprint data=dat5;
var PowerPeach;
by BoatClass Gender BoatID StrokeSet;
*where Side="B";
output out=meansd mean=WthnBoatMean std=WthnBoatSD;

proc means maxdec=1;
var WthnBoatMean WthnBoatSD;
class BoatClass Gender;
run;

title "Within-boat simple stats for log-transformed StrokeRate";
title2 "Nobs is the number of stroke sets";
```

```
proc means noprint data=dat5;
var StrokeRate;
by BoatClass Gender BoatID StrokeSet;
*where Side="B";
output out=meansd mean=WthnBoatMean std=WthnBoatSD;

proc means maxdec=1;
var WthnBoatMean WthnBoatSD;
class BoatClass Gender;
run;

*make macrovariables holding values of 2 within-StrokeSet SD averaged across all
boats;
*title3 "(the log-transformed value for SDx2 is used via macro variables)";
proc standard data=dat5 out=datsd mean=0;
var PowerPeach StrokeRate;
by BoatClass Gender BoatID StrokeSet;

title "Mean within-StrokeSet SD and SDx2 (%) PowerPeach";
title2 "SDx2 is used to estimate magnitude of the effect of PowerPeach";
proc means noprint data=datsd;
var PowerPeach;
by BoatClass Gender;
output out=datsd1 std=WthnSD;

data datsd2;
set datsd1;
by BoatClass Gender;
WthnSDx2=2*WthnSD;
if BoatClass="2-" then BoatClass="2m"; *cannot have - in a macro variable name;
MacroVariable="Power"||Gender||BoatClass||"SDx2";
call symput(MacroVariable,left(round(WthnSDx2,1)));
WthnSD=100*exp(WthnSD/100)-100;
WthnSDx2=100*exp(WthnSDx2/100)-100;
run;

proc print noobs;
var BoatClass Gender WthnSD WthnSDx2 MacroVariable;
format WthnSD WthnSDx2 5.0;
run;

title "Mean within-boat within-StrokeSet SD and SDx2 (%) StrokeRate";
title2 "SDx2 is used to estimate magnitude of the effect of StrokeRate";
proc means noprint data=datsd;
var StrokeRate;
by BoatClass Gender;
output out=datsd1 std=WthnSD;

data datsd2;
set datsd1;
```

```
by BoatClass Gender;
WthnSDx2=2*WthnSD;
if BoatClass="2-" then BoatClass="2m"; *cannot have - in a macro variable name;
MacroVariable="StrokeRate"||Gender||BoatClass||"SDx2";
call symput(MacroVariable,left(round(WthnSDx2,0.1)));
WthnSD=100*exp(WthnSD/100)-100;
WthnSDx2=100*exp(WthnSDx2/100)-100;
run;

proc print noobs;
var BoatClass Gender WthnSD WthnSDx2 MacroVariable;
format WthnSD WthnSDx2 5.1;
run;

/*
*check;
data;
M1xSDx2=&M1xSDx2;
W2mSDx2=&W2mSDx2;

proc print;run;
*/

*title "Between- and within-boat simple stats";
*title2 "Nobs is the number of boats";
*use the PowerPeach and StrokeRate means to standardize to a mean of zero;
proc means noprint data=dat5;
var &dep PowerPeach StrokeRate;
by BoatClass Gender BoatID;
*where Side="B";
output out=predboatmean mean=&dep.Mean PowerPeachMean StrokeRateMean; *
std=WthnBoatSD;

title "Between-boat simple stats for mean of log-transformed &dep PowerPeach and
StrokeRate";
title2 "Compare the SDs: we expect SD for PowerPeach to be more than 3x the SD for
AvBoatVel";
title3 "N is the number of boats";
proc means maxdec=1 data=predboatmean n mean std min max;
var &dep.Mean PowerPeachMean StrokeRateMean;
class BoatClass Gender;
run;

proc means noprint data=predboatmean;
var PowerPeachMean StrokeRateMean;
by BoatClass Gender;
output out=predboatmean1(drop=_type_ _freq_) mean=;

*add strokeset to Power1;
proc sort data=dat5;
```

```
by BoatClass Gender BoatID Event Race StrokeSet;

proc means noprint data=dat5;
var &dep; *can be anything numeric;
by BoatClass Gender BoatID Event Race StrokeSet;
output out=temp1(drop=_freq_ _type_) mean=;

proc sort data=power1;
by BoatClass Gender BoatID Event Race;

data power2;
merge temp1(drop=&dep) power1;
by BoatClass Gender BoatID Event Race;
run;

*get BoatPower and StrokeRate means for each race to make a prediction dataset;
data predict;
set Power2(keep=BoatClass Gender BoatID Event Race StrokeSet RaceTime
StrokeRate BoatPower
  rename=(BoatPower=PowerPeach0 StrokeRate=StrokeRate0));
StrokeRate0=100*log(StrokeRate0);
PowerPeach0=100*log(PowerPeach0);
&dep=.;
*StrokeSet=100+_n_;
do PowerExtraPC=0 to 20 by 5;
  do StrokeExtraPC=0 to 10 by 2.5;
    PowerPeach=PowerPeach0+PowerExtraPC;
    PowerPredictor=exp(PowerPeach/100); *need this because standardize PowerPeach;
    StrokeRate=StrokeRate0+StrokeExtraPC;
    StrokeRatePredictor=exp(StrokeRate/100); *ditto StrokeRate;
    output;
    end;
  end;
drop StrokeRate0 PowerPeach0;
format PowerPredictor 5.0 StrokeRatePredictor 5.1;
run;

data dat6;
set dat5 predict;
*merge dat5 predboatmean2(keep=BoatClass Gender BoatID &predboat.Mean
&predboat.MeanResc);
*by BoatClass Gender BoatID;
run;

*now standardize PowerPeach and StrokeRate to means of zero;
proc sort data=dat6;
by BoatClass Gender StrokeSet; * BoatID StrokeSet;
run;

data dat6a;
```

```
merge dat6 predboatmean1;
by BoatClass Gender;
PowerPeach=PowerPeach-PowerPeachMean;
StrokeRate=StrokeRate-StrokeRateMean;
HeadWind=WindAve*cos((WindDirectionDec-1)*2*3.14159/12);
run;

title "Simple stats for HeadWind";
title2 "N is number of races";
proc means noprint data=dat6a;
var HeadWind;
by BoatClass Gender StrokeSet;
output out=wind mean=HeadWindMean std=HeadWindSD;

proc means maxdec=1 n mean std min max;
var HeadWindMean HeadWindSD;
class BoatClass Gender;
run;

data dat7;
merge dat6a wind(drop=_freq_ _type_ HeadWindSD);
by BoatClass Gender StrokeSet;
HeadWindSq=sign(HeadWindMean)*HeadWindMean**2;
run;
/*
title "Within-boat correlations";
ods select none;
proc corr data=dat5 nosimple outp=corrs;
var AvBoatVel PowerPeach &predboat;
by BoatClass Gender BoatID StrokeSet;
*ods output FisherPearsonCorr=fish;
run;
ods select all;

*proc print data=corrs(obs=20);run;

data corrs1;
retain SortOrder;
set corrs;
if _Type_="CORR";
drop _type_ ;
if _name_ ne "";
if _name_="AvBoatVel" then SortOrder=0;
if lag(_name_) ne _name_ then SortOrder=SortOrder+1;
rename _name_=Predictor;
array a AvBoatVel PowerPeach &predboat;
do over a;
  if a=1 then a=.;
  end;
```

```
proc sort;
by BoatClass Gender SortOrder Predictor;

proc means noprint;
var AvBoatVel PowerPeach &predboat;
by BoatClass Gender SortOrder Predictor;
output out=corrs2 mean=;
run;

proc print noobs;
var BoatClass Gender Predictor AvBoatVel PowerPeach &predboat;
by BoatClass Gender;
format _numeric_ 5.2;
run;
*/
/*
proc freq data=dat4;
tables Participant*Race/nocol norow nopercent nocum;
by BoatClass Gender;
run
*/
/*
proc print data=dat3; *(obs=10);
where BoatID ne "VRMLM1x";
run;
*/
/*
data pdata;
Gender="M"; BoatClass="1x";
estimate=6;output;estimate=2;output; output;
estimate=9;output;estimate=5;output;estimate=10;output;estimate=6;output;
do i=1 to 6;
  estimate=5;
  output;
  end;
Gender="M"; BoatClass="2-";
do i=1 to 7;
  estimate=5;
  output;
  end;
Gender="W"; BoatClass="1x";
do i=1 to 10;
  estimate=5;
  output;
  end;
Gender="W"; BoatClass="2-";
do i=1 to 13;
  estimate=5;
  output;
  end;
```

```
keep BoatClass Gender estimate;
*/
/*
proc univariate plot data=dat4;
var DriveAccelMax;
class Participant;
by BoatClass Gender;
run;
*/
/*
proc sort data=dat4;
by BoatClass Gender Participant Side;

proc standard data=dat4 mean=0 out=dat5;
var &pred;
by BoatClass Gender Participant;
run;

title "100*log(&pred), simple stats with each participlant rescaled to zero";
proc means maxdec=0 data=dat5;
var &pred;
class BoatClass Gender;
run;
*/
*proc print data=dat5(obs=500);run;

/*
proc standard data=dat6 out=dat7 mean=0;
var &predboat;
by BoatClass Gender BoatID;

proc standard data=dat7 out=dat8 std=0.5;
var &predboat;
by BoatClass Gender;
run;
*/
/*
proc standard data=dat6 out=dat9 mean=0;
var PowerPeach;
by BoatClass Gender;
run;

proc standard data=dat9 out=dat10 mean=0;
var StrokeRate;
by BoatClass Gender BoatID StrokeSet;

proc standard data=dat10 out=dat11 std=0.5;
var StrokeRate;
by BoatClass Gender;
run;
```

```
*/
/*
proc print data=dat11;
where PowerPeach*StrokeRate*StrokeSet=. or BoatID="" or Race="";
run;
*8 observations here, a smattering of individual strokes missing PowerPeachBow;
*/

data cov lsm lsmdiff lsmdiff1 lsmdiff2  lsmest est solf solr pred pred1;

%let convcrit=CONVH=1E-8 convf=1E-8;

ods select none;
*ods listing close;
proc mixed data=dat7 covtest cl alpha=&alpha &nob &convcrit;
class BoatID Race StrokeSet;
*model &dep=PowerPeach StrokeRate HeadWindMean HeadWindSq/outp=pred s
residual ddfm=sat alphap=&alpha; *better without ddfm=sat?;
model &dep=PowerPeach StrokeRate HeadWindMean/outp=pred s residual ddfm=sat
alphap=&alpha; *better without ddfm=sat?;
*model &dep=PowerPeach &predboat/outp=pred s residual ddfm=sat alphap=&alpha
ddfm=sat; *better without ddfm=sat?;
*model &dep=PowerPeach &predboat.MeanResc &predboat/outp=pred s residual
ddfm=sat alphap=&alpha ddfm=sat; *better without ddfm=sat?;
*model &dep=PowerCubRoot PowerCubRoot*PowerCubRoot/outp=pred s residual
ddfm=sat alphap=&alpha ddfm=sat; *better without ddfm=sat?;
*estimate "Intercept" int 1/cl alpha=&alpha;
*estimate "HeadWindMean /(1m/s)" HeadWindMean 1 HeadWindSq 1/cl
alpha=&alpha;
*estimate "HeadWindMean /(2m/s)" HeadWindMean 2 HeadWindSq 4/cl
alpha=&alpha;
estimate "HeadWindMean /(1m/s)" HeadWindMean 1/cl alpha=&alpha;
estimate "HeadWindMean /(2m/s)" HeadWindMean 2/cl alpha=&alpha;
estimate "PowerPeach /%" PowerPeach 1/cl alpha=&alpha;
estimate "StrokeRate /%" StrokeRate 1/cl alpha=&alpha;
estimate "PowerPeach /2SD:";
estimate "Power M1x per &PowerM1xSDx2" PowerPeach &PowerM1xSDx2/cl
alpha=&alpha;
estimate "Power M2- per &PowerM2mSDx2" PowerPeach &PowerM2mSDx2/cl
alpha=&alpha;
estimate "Power W1x per &PowerW1xSDx2" PowerPeach &PowerW1xSDx2/cl
alpha=&alpha;
estimate "Power W2- per &PowerW2mSDx2" PowerPeach &PowerW2mSDx2/cl
alpha=&alpha;
estimate "StrokeRate /2SD:";
estimate "StrokeRate M1x per &StrokeRateM1xSDx2" StrokeRate
&StrokeRateM1xSDx2/cl alpha=&alpha;
estimate "StrokeRate M2- per &StrokeRateM2mSDx2" StrokeRate
&StrokeRateM2mSDx2/cl alpha=&alpha;
```

```
estimate "StrokeRate W1x per &StrokeRateW1xSDx2" StrokeRate
&StrokeRateW1xSDx2/cl alpha=&alpha;
estimate "StrokeRate W2- per &StrokeRateW2mSDx2" StrokeRate
&StrokeRateW2mSDx2/cl alpha=&alpha;
*estimate "PowerCubRoot /%" PowerCubRoot 1/cl alpha=&alpha;
*estimate "PowerCubRoot^2 /%^2" PowerCubRoot*PowerCubRoot 1/cl alpha=&alpha;
*estimate "&predboat.Mean 2SD" &predboat.MeanResc 1/cl alpha=&alpha;
*estimate "&predboat 2SD" &predboat 1/cl alpha=&alpha;
*random int &predboat/subject=BoatID type=un s cl alpha=&alpha;
random int PowerPeach StrokeRate/subject=BoatID s cl alpha=&alpha type=un;
*random PowerPeach/subject=BoatID s cl alpha=&alpha;
random StrokeSet/subject=BoatID s cl alpha=&alpha;
*random StrokeSet Date/s cl alpha=&alpha;
*random &predboat/subject=BoatID s cl alpha=&alpha;
repeated/group=StrokeSet*BoatID;
/*
lsmestimate Device*SerialNumber "NK-Vicon:" 0;
lsmestimate Device*SerialNumber
  "Unit 1100827" 1 0 0 0  0 0 0  0 0 0  -1 0 0 0,
  "Unit 1101134" 0 1 0 0  0 0 0  0 0 0  0 -1 0 0,
  "Unit 1101819" 0 0 1 0  0 0 0  0 0 0  0 0 -1 0,
  "Unit 1101823" 0 0 0 1  0 0 0  0 0 0  0 0 0 -1
  /cl alpha=0.1;
*/
*&parms;
*parms 5 5  5 5 5 5 5 5 5 5 5 5 5;
*parms/pdata=pdata;
ods output classlevels=clev;
ods output covparms=cov;
ods output lsmeans=lsm;
ods output diffs=lsmdiff;
ods output estimates=est;
ods output solutionf=solf;
ods output solutionr=solr;
ods output lsmestimates=lsmest;
by BoatClass Gender;
*where &dep ne .;
*where Gender="W" and BoatClass="2-";
*where Gender="M" and BoatClass="1x";
run;
ods select all;

&title1;
title2 "Class levels; Race not currently in the model";
*title3 "StrokeSet=0 is for boat predicted means";
proc print data=clev noobs; run;

title2 "Random effects, to check on adequacy of the model";
proc print data=cov noobs;
by BoatClass Gender;
```

```
run;

*proc print data=clev;run;
*proc print data=cov;run;
*proc print data=est;run;
*by BoatClass Gender;
run;

*proc print data=cov;run;
/*
proc print data=clev;run;
proc print data=cov;run;
proc print data=est;run;


proc print data=lsm;run;
proc print data=solr;run;
proc print data=decodeset;run;
*by BoatClass Gender;
run;
*/

data pred1;
set pred;
/*
if &logflag then do;
  *&pred=exp(&pred/100);
  &dep=exp(&dep/100);
  pred=exp(pred/100);
  end;
*/

*proc print data=pred;run;

title2 "Raw residuals vs predicteds";
*title2 "Standardized residuals vs predicteds";
/*options ls=80 ps=36;
proc plot data=pred1;
plot StudentResid*pred;
by BoatClass Gender;
run;
*/
proc sort data=pred1;
by BoatClass Gender StrokeSet;

ods graphics / reset width=12cm height=10cm imagemap attrpriority=none;
proc sgplot data=pred1; *uniform=all;
scatter x=pred y=Resid/markerattrs=(size=3 color=black symbol=circlefilled)
filledoutlinedmarkers MARKERFILLATTRS=(color=black);
```

```
*scatter x=StrokeNo y=Resid/markerattrs=(size=3 color=black symbol=circlefilled)
filledoutlinedmarkers MARKERFILLATTRS=(color=black);
refline 0/axis=y lineattrs=(pattern=dot thickness=1 color=blue);
by BoatClass Gender;
*where Gender="M" and BoatClass="2-" and StrokeSet=36;
run;
ods graphics / reset;
/*
proc plot data=pred1;
plot (&dep &pred)*StrokeNo;
by BoatClass Gender StrokeSet Side;
where Gender="M" and BoatClass="2-" and StrokeSet=36;
run;

options ps=52 ls=100;
proc print data=pred1;
var BoatClass Gender BoatID Date Race StrokeSet StrokeNo AvBoatVel &dep  pred
resid Studentresid;
format &dep pred 5.&decdep studentresid 5.1;
by BoatClass Gender;
where Resid<-200;
*where Gender="M" and BoatClass="2-" and StrokeSet=36;
run;
*/
option ls=90;
options ls=100 ps=50;
data pred2;
set pred1;
if abs(StudentResid)>4.5;

options ps=52 ls=100;
proc print data=pred2;
var BoatClass Gender BoatID Date Race StrokeSet StrokeNo &dep pred resid
Studentresid;
title2 "Outliers (Standardized residual >4.5)";
format &dep 5.&decdep studentresid 5.1;
by BoatClass Gender;
run;
option ls=90;

/*
proc sort data=pred1;
by descending PredictAt BoatClass Gender ;

proc print data=pred1;
var PredictAt Gender BoatID BoatClass StrokeSet PredictAt Race AvBoatVel
PredictedPower CLpm DF      Alpha Lower   Upper;
format AvBoatVel 5.1 PredictedPower CLpm DF     Lower  Upper 5.0;
by descending PredictAt BoatClass Gender;
run;
```

```
*/

*thresholds via given smallest important;
data thresholds;
*set stdsd;
Units="Raw";
if &logflag then Units="%";
magnithresh=&MagniThresh;
if &logflag=0 then do; *these raw thresholds are actually via standardization;
Threshold="small   "; DeltaMeanBene=magnithresh; DeltaMeanHarm=-magnithresh;
SDthreshold=abs(magnithresh)/2; output;
  Threshold="moderate"; DeltaMeanBene=magnithresh*3; DeltaMeanHarm=-
magnithresh*3; SDthreshold=abs(DeltaMeanBene)/2; output;
  Threshold="large"; DeltaMeanBene=magnithresh*6; DeltaMeanHarm=-
magnithresh*6; SDthreshold=abs(DeltaMeanBene)/2; output;
  Threshold="vlarge"; DeltaMeanBene=magnithresh*10; DeltaMeanHarm=-
magnithresh*10; SDthreshold=abs(DeltaMeanBene)/2; output;
  Threshold="xxlarge"; DeltaMeanBene=magnithresh*20; DeltaMeanHarm=-
magnithresh*20; SDthreshold=abs(DeltaMeanBene)/2; output;
  end;
else do;
  magnithresh=100*log(1+magnithresh/100);
  Threshold="small   "; DeltaMeanBene=100*exp(magnithresh/100)-100;
DeltaMeanHarm=100*exp(-magnithresh/100)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2)-100; output;
  Threshold="moderate"; DeltaMeanBene=100*exp(magnithresh/100*3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*3)-100; output;
  Threshold="large"; DeltaMeanBene=100*exp(magnithresh/100*1.6/0.3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*1.6/0.3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*1.6/0.3)-100; output;
  Threshold="vlarge"; DeltaMeanBene=100*exp(magnithresh/100*2.5/0.3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*2.5/0.3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*2.5/0.3)-100; output;
  Threshold="xlarge"; DeltaMeanBene=100*exp(magnithresh/100*4.0/0.3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*4.0/0.3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*4.0/0.3)-100; output;
  end;

title2 "&dep magnitude thresholds (&unitsrawlog), based on a given smallest important
for means of &magnithresh (&unitsrawlog).";
title3 "Factors for the thresholds for moderate, large, v.large and x.large are .9/.3x,
1.6/.3x, 2.5/.3x and 4/.3x the smallest important,";
title4 "i.e., competitive athlete thresholds; thresholds for SDs are half those for means.";
proc print noobs;
var Threshold Units DeltaMeanBene DeltaMeanHarm SDthreshold;
format DeltaMeanBene DeltaMeanHarm SDthreshold 5.&decdep;format
DeltaMeanBene DeltaMeanHarm SDthreshold 5.&decdep;
where &logflag=0;
run;
```

```
proc print noobs;
var Threshold Units DeltaMeanBene DeltaMeanHarm SDthreshold;
format DeltaMeanBene DeltaMeanHarm 5.&deceff SDthreshold 5.2;
where &logflag=1;
run;

*make macro variables for magnitude thresholds for the MBD steps;
data _null_;
length ThreshX $ 9;
set thresholds;
if &logflag then Thresh=abs(100*log(1+DeltaMeanBene/100)); *convert back to log
value, could do it with DeltaMeanHarm;
else Thresh=abs(DeltaMeanBene);
ThreshX=trim(Threshold)||'X';
call symput(ThreshX,Thresh);
run;
/*
data check;
Smallvalue=&smallx;
Modvalue=&moderatex;

proc print;run;
*/

data est1;
set est;
if estimate=0 then estimate=.;
GenderBoatClass=Gender||BoatClass;
*if index(Label,"per") and substr(Label,1,3) ne GenderBoatClass then delete;
if index(Label,GenderBoatclass) or index(Label,"/%") or index(Label,"HeadWind");
array a estimate lower upper;
if &logflag=1 then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(upper-lower)/2;
*if index(Label,"RFDAv") and index(Label,BoatClass)=0 then delete;

proc sort;
by label;

title2 "Fixed effects (&unitsrawlog)";
title3 "Effect of 1 and 2 m/s of headwind";
proc print data=est1 noobs;
var BoatClass Gender label Estimate CLpm Lower Upper DF alpha;
format estimate CLpm lower upper 5.2;
by Label;
where index(Label,"HeadWind");
run;
```

```
*title3 "Ignore the intercept, the PowerPeach is the index in V=kP^x";
title3 "PowerPeach and StrokeRate are the index x and y in V=k.P^x.SR^y";
proc print data=est1 noobs;
var BoatClass Gender label Estimate CLpm Lower Upper DF alpha;
format estimate CLpm lower upper 5.2;
*by Label;
where index(Label,"/%") and index(Label,"Power");
run;

proc print data=est1 noobs;
var BoatClass Gender label Estimate CLpm Lower Upper DF alpha;
format estimate CLpm lower upper 5.2;
*by Label;
where index(Label,"/%") and index(Label,"Stroke");
run;

title3 "Effect of 2 within-strokeset SD of PowerPeach and StrokeRate";
proc print data=est1 noobs;
var BoatClass Gender label Estimate CLpm Lower Upper DF alpha;
format estimate CLpm lower upper 5.1;
*by Label;
where index(Label,"per") and index(Label,"Power");
run;

proc print data=est1 noobs;
var BoatClass Gender label Estimate CLpm Lower Upper DF alpha;
format estimate CLpm lower upper 5.1;
*by Label;
where index(Label,"per") and index(Label,"Stroke");
run;

title3 "MBD for fixed effects with a given smallest important for means of
&magnithresh (&unitsrawlog)";
data est1;
set est;
GenderBoatClass=Gender||BoatClass;
if index(Label,GenderBoatclass) or index(Label,"HeadWind");
*if index(Label,"per") and substr(Label,1,3) ne GenderBoatClass then delete;
*if Label="PowerPeach /%" then delete;
*if index(Label,"2SD");
length Prob $ 8 Magni $ 4 QualMag $ 8;
QualMag="Trivial";
if abs(estimate)>&smallx then QualMag="Small";
if abs(estimate)>&moderatex then QualMag="Moderate";
if abs(estimate)>&largex then QualMag="Large";
if abs(estimate)>&vlargex then QualMag="Vlarge";
if abs(estimate)>&xlargex then QualMag="Xlarge";
MagniThresh=&MagniThresh;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh))/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh))/StdErr,DF);
```

```
if &LogFlag=1 then do;
  if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  else do;
    ChancePos=100*(1-ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  end;

ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
ClinFlag=1; *want inferences to be clinical;
*if index(label,"2SD") then ClinFlag=0; *covariates definitely need to be non-clinical;
*clinical inferences;
if clinflag then do;
Precision="unclear";
ChPos=ChancePos; ChNeg=ChanceNeg;
if MagniThresh<0 then do;
  ChPos=ChanceNeg; ChNeg=ChancePos;
  end;
if ChNeg<0.5 then do;
  Precision="@25/.5%";
  if ChNeg<0.1 then Precision="@5/.1% ";
  Magni="bene";
  if ChNeg<0.1 and ChPos>5 then Prob="unlikely";
  if ChPos>25 then Prob="possibly";
  if ChPos>75 then Prob="likely  ";
  if ChPos>95 then Prob="v.likely";
  if ChPos>99.5 then Prob="m.likely";
  if ChPos<25 and prob ne "unlikely" then do;
    Magni="triv";
    if ChanceTriv>25 then Prob="possibly";
    if ChanceTriv>75 then Prob="likely  ";
    if ChanceTriv>95 then Prob="v.likely";
    if ChanceTriv>99.5 then Prob="m.likely";
    end;
  end;
else do; *ChNeg>0.5;
  if ChPos<25 then do;
    Precision="@25/.5%";
    if ChPos<5 then Precision="@5/.1% ";
    if ChanceTriv>25 then do;
      Magni="triv";Prob="possibly";
      if ChanceTriv>75 then Prob="likely";
      if ChanceTriv>95 then Prob="v.likely";
      if ChanceTriv>99.5 then Prob="m.likely";
      end;
```

```
    if ChNeg>25 then do;
      Magni="harm";Prob="possibly";
      if ChNeg>75 then Prob="likely  ";
      if ChNeg>75 then Prob="likely  ";
      if ChNeg>95 then Prob="v.likely";
      if ChNeg>99.5 then Prob="m.likely";
      end;
    end;
  end;
if Precision="unclear" and
  (MagniThresh>0 and ORPosNeg>25/75/(0.5/99.5) or StdzedMagniThresh<0 and
ORNegPos>25/75/(0.5/99.5))
  then do;
  Precision="OR>66.3";
  Magni="bene";
  if ChPos>25 then Prob="possibly";
  if ChPos>75 then Prob="likely  ";
  if ChPos>95 then Prob="v.likely";
  if ChPos>99.5 then Prob="m.likely";
  end;
output;
end;
*mechanistic inferences;
ClinFlag=0;
Precision="unclear";
Prob="";
Magni="     ";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then Precision="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then Precision="@99%  ";
if Precision ne "unclear" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if Precision ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
*end;
output;

data est2;
set est1;
```

```
if estimate=0 or estimate=. then do;
  estimate=.; magnithresh=.; magni=""; Precision=""; Prob=""; Units=""; Magni="";
Precision=.; QualMag="";
  end;
array a estimate lower upper;
if &logflag then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(Upper-lower)/2;
rename df=DegFree;
if index(Label,".")=1 then Label=substr(Label,2);
run;

proc sort;
by Label;

*options ls=135 ps=80;
title4 "Units for estimates, confidence limits and smallest important are &unitsrawlog";
title5 "Non-clinical inferences";
proc print data=est2 noobs;
where clinflag=0 and index(Label,"HeadWind");
var BoatClass Gender label estimate CLpm lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos QualMag Prob Magni Precision;
format estimate CLpm lower upper MagniThresh 5.&deceff Probt best5. ChanceNeg
ChanceTriv
  ChancePos 5.1 DegFree 5.0;
by label;
*where index(Label,"per") and clinflag=0;
run;

proc print data=est2 noobs;
where clinflag=0 and index(Label,"per") and index(Label,"Power");
var BoatClass Gender label estimate CLpm lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos QualMag Prob Magni Precision;
format estimate CLpm lower upper MagniThresh 5.&deceff Probt best5. ChanceNeg
ChanceTriv
  ChancePos 5.1 DegFree 5.0;
*by BoatClass Gender;
*where index(Label,"per") and clinflag=0;
run;

proc print data=est2 noobs;
where clinflag=0 and index(Label,"per") and index(Label,"Stroke");
var BoatClass Gender label estimate CLpm lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos QualMag Prob Magni Precision;
format estimate CLpm lower upper MagniThresh 5.&deceff Probt best5. ChanceNeg
ChanceTriv
  ChancePos 5.1 DegFree 5.0;
*by BoatClass Gender;
*where index(Label,"per") and clinflag=0;
```

```
run;
/*
proc print data=est2 noobs;
*where clinflag=0;
var BoatClass Gender label estimate CLpm lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos Prob Magni Precision;
format estimate CLpm lower upper MagniThresh 5.&deceff Probt best5. ChanceNeg
ChanceTriv
  ChancePos 5.1 DegFree 5.0;
*by BoatClass Gender;
where index(Label,"StrokeRate") and clinflag=0;
run;
*/

data covall0;
length covparm $ 15;
set cov;
if covparm="UN(2,1)" or covparm="UN(3,1)" or covparm="UN(3,2)" then delete;
if covparm="UN(1,1)" then covparm="Intercept";
if covparm="UN(2,2)" then covparm="PowerPeach";
if covparm="UN(3,3)" then covparm="StrokeRate";
output;
if covparm="PowerPeach" then do;
  covparm="PowerPeach x2SD";
  if Gender="M" and BoatClass="1x" then factor=&PowerM1xSDx2**2;
  if Gender="M" and BoatClass="2-" then factor=&PowerM2mSDx2**2;
  if Gender="W" and BoatClass="1x" then factor=&PowerW1xSDx2**2;
  if Gender="W" and BoatClass="2-" then factor=&PowerW2mSDx2**2;
  estimate=estimate*factor;
  StdErr=StdErr*factor;
  output;
  end;
if covparm="StrokeRate" then do;
  covparm="StrokeRate x2SD";
  if Gender="M" and BoatClass="1x" then factor=&StrokeRateM1xSDx2**2;
  if Gender="M" and BoatClass="2-" then factor=&StrokeRateM2mSDx2**2;
  if Gender="W" and BoatClass="1x" then factor=&StrokeRateW1xSDx2**2;
  if Gender="W" and BoatClass="2-" then factor=&StrokeRateW2mSDx2**2;
  estimate=estimate*factor;
  StdErr=StdErr*factor;
  output;
  end;

data covall;
set covall0;
alpha=&alpha;
DegFree=2*ZValue**2;
*if Lower=. then do;
  *Lower=DegFree*estimate/CINV(1-alpha/2,DegFree);
  *Upper=DegFree*estimate/CINV(alpha/2,DegFree);
```

```
  *conf limits via normal dist;
if StdErr ne 0 then do;
  lower=estimate+probit(alpha/2)*StdErr;
  upper=estimate-probit(alpha/2)*StdErr;
  end;
array a estimate lower upper;
do over a;
  a=sign(a)*sqrt(abs(a));
  end;
if &logflag=1 then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(upper-lower)/2;
*if substr(covparm,1,2) ne "UN" then CLpm=(upper-lower)/2;
CLtd=sqrt(upper/lower);
drop StdErr--ProbZ;
Group=substr(Group,8);

title2 "Random effects as standard deviations (&unitsrawlog)";
title3 "Intercept is boat indiv differences in mean efficiency";
title4 "PowerPeach and StrokeRate are indiv. diffs in the index x and y in
V=k.P^x.SR^y";
*title4 "&predboat is boat indiv differences in slope";
title5 "StrokeSet is boat mean differences between races, e.g., due to changes in
environment";
*title5 "Date is mean differences between dates, e.g., due to changes in environment";
title6 "Residual is the stroke to stroke variation in speed";
proc print noobs data=covall;
var BoatClass Gender covparm subject Group estimate CLpm lower upper alpha;
format estimate lower upper CLpm 5.&deceff CLtd 5.2 DegFree 5.0;
by BoatClass Gender;
where index(covparm,"x2SD")=0;
run;

*get residuals identified by StrokeSet;
data resid;
set cov;
if covparm="Residual";
if index(Group,"x") then StrokeSet=0+substr(Group,index(Group,"x")+2);
if index(Group,"-") then StrokeSet=0+substr(Group,index(Group,"-")+2);
keep BoatClass Gender Estimate StrokeSet;
Estimate=sqrt(Estimate);
rename Estimate=Variability;

*proc print data=cov;run;

title3 "Intercept is boat indiv differences in mean efficiency";
proc print noobs data=covall;
var BoatClass Gender covparm subject  estimate CLpm lower upper alpha;
format estimate lower upper CLpm 5.2 CLtd 5.2 DegFree 5.0;
```

```
*by BoatClass Gender;
where covparm="Intercept";
run;

title3 "PowerPeach (%/%) is boat indiv differences in x, where V=k.P^x.SR^y";
proc print noobs data=covall;
var BoatClass Gender covparm subject  estimate CLpm lower upper alpha;
format estimate lower upper CLpm 5.2 CLtd 5.2 DegFree 5.0;
*by BoatClass Gender;
where covparm="PowerPeach";
run;

title3 "PowerPeach x2SD is random effect for 2 within-strokeset SD";
proc print noobs data=covall;
var BoatClass Gender covparm subject  estimate CLpm lower upper alpha;
format estimate lower upper CLpm 5.1 CLtd 5.2 DegFree 5.0;
*by BoatClass Gender;
where covparm="PowerPeach x2SD";
run;

title3 "StrokeRate (%/%) is boat indiv differences in y, where V=k.P^x.SR^y";
proc print noobs data=covall;
var BoatClass Gender covparm subject  estimate CLpm lower upper alpha;
format estimate lower upper CLpm 5.2 CLtd 5.2 DegFree 5.0;
*by BoatClass Gender;
where covparm="StrokeRate";
run;

title3 "StrokeRate x2SD is random effect for 2 within-strokeset SD";
proc print noobs data=covall;
var BoatClass Gender covparm subject  estimate CLpm lower upper alpha;
format estimate lower upper CLpm 5.1 CLtd 5.2 DegFree 5.0;
*by BoatClass Gender;
where covparm="StrokeRate x2SD";
run;

title3 "StrokeSet is boat mean differences between races, e.g., due to changes in
environment";
proc print noobs data=covall;
var BoatClass Gender covparm subject  estimate CLpm lower upper alpha;
format estimate lower upper CLpm 5.2 CLtd 5.2 DegFree 5.0;
*by BoatClass Gender;
where covparm="StrokeSet";
run;

title2 "MBD for random effects with a given smallest important for means of
&magnithresh (&unitsrawlog)";
title3 "Intercept is boat indiv differences in mean efficiency";
title4 "PowerPeach x2SD is random effect for 2 within-strokeset SD";
title5 "StrokeRate x2SD is random effect for 2 within-strokeset SD";
```

```
title6 "StrokeSet is boat mean differences between races, e.g., due to changes in
environment";
title7 "Residual is the stroke to stroke variation in speed";
data cov1;
set covall0;
if covparm="PowerPeach" or covparm="StrokeRate" then delete;
QualMag="Trivial ";
if sqrt(abs(estimate))>&smallx/2 then QualMag="Small";
if sqrt(abs(estimate))>&moderatex/2 then QualMag="Moderate";
if sqrt(abs(estimate))>&largex/2 then QualMag="Large";
if sqrt(abs(estimate))>&vlargex/2 then QualMag="Vlarge";
if sqrt(abs(estimate))>&xlargex/2 then QualMag="Xlarge";
*if covparm="UN(1,1)" then covparm="Intercept";
*if covparm="UN(2,2)" then covparm="PowerPeach";
*if covparm="UN(2,1)" or covparm="Residual" or covparm="PowerPeach" then delete;
*if substr(Group,8)="NK" or substr(Group,8)="Peach"; *add or modify, depending on
the analysis;
*lower=estimate+probit(alpha/2)*StdErr; *for those models where nobound did not
work;
*upper=estimate-probit(alpha/2)*StdErr;
DF=999;
MagniThresh=abs(&MagniThresh)/2;
if &logflag then Magnithresh=100*exp(log(1+abs(&magnithresh)/100)/2)-100;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh)**2)/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh)**2)/StdErr,DF);
if &logflag then do;
  *if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-
(100*log(1+MagniThresh/100))**2)/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+(100*log(1+MagniThresh/100))**2)/StdErr,DF);
    end;
ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
*ClinFlag=0; *want all inferences to be non-clinical for within-subject random effect;
*mechanistic inferences;
Precision="unclear";
Prob="        ";
Magni="     ";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then Precision="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then Precision="@99%  ";
if Precision ne "unclear" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
```

```
  end;
if Precision ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
if not stderr then do; Magni="";Precision=""; end;
Group=substr(Group,8);

data cov2;
set cov1;
alpha=&alpha;
*if covparm ne "Residual" then do;
  lower=estimate+probit(alpha/2)*StdErr;
  upper=estimate-probit(alpha/2)*StdErr;
*  end;
array a estimate lower upper;
do over a;
  a=sign(a)*sqrt(abs(a));
  end;
DegFree=2*Zvalue**2;
array r SD lower upper;
if &logflag=1 then do over r;
  r=100*exp(r/100)-100;
  end;
CLpm=(upper-lower)/2;
*if substr(covparm,1,2) ne "UN" then CLpm=(upper-lower)/2;
CLtd=sqrt(upper/lower);
run;

proc sort;
by covparm;

title8 "Non-clinical MBD for SD representing random effects";
title9 "Magnithresh is half the given smallest difference for means";
proc print data=cov2 noobs;
var BoatClass Gender covparm Subject Group estimate CLpm lower upper alpha
  MagniThresh ChanceNeg ChanceTriv ChancePos QualMag Prob Magni Precision;
format estimate CLpm lower upper 5.&deceff MagniThresh 5.2 ChanceNeg ChanceTriv
  ChancePos 5.1 DF 5.0;
*by BoatClass Gender;
by covparm;
where covparm ne "Residual";
run;

title8 "Non-clinical MBD for SD representing random effects";
title9 "Magnithresh is half the given smallest difference for means";
proc print data=cov2 noobs;
var BoatClass Gender covparm Subject Group estimate CLpm lower upper alpha
```

```
  MagniThresh ChanceNeg ChanceTriv ChancePos QualMag Prob Magni Precision;
format estimate CLpm lower upper 5.&deceff MagniThresh 5.2 ChanceNeg ChanceTriv
  ChancePos 5.1 DF 5.0;
by BoatClass Gender;
where covparm="Residual";
run;

*proc print data=solr;run;
*random-effect solution;
data solr1;
set solr;
/*
Alpha=&alpha;
t=tinv(1-&alpha/2,DF);
LowerCL=Estimate-t*StdErrPred;
UpperCL=Estimate+t*StdErrPred;
*/
if effect="Intercept" or effect="StrokeSet" or effect="PowerPeach" or
effect="StrokeRate";
array a Estimate StdErrPred Lower Upper;
if effect="PowerPeach" then do over a;
  if Gender="M" and BoatClass="1x" then factor=&PowerM1xSDx2;
  if Gender="M" and BoatClass="2-" then factor=&PowerM2mSDx2;
  if Gender="W" and BoatClass="1x" then factor=&PowerW1xSDx2;
  if Gender="W" and BoatClass="2-" then factor=&PowerW2mSDx2;
  a=a*factor;
  end;
if effect="StrokeRate" then do over a;
  if Gender="M" and BoatClass="1x" then factor=&StrokeRateM1xSDx2;
  if Gender="M" and BoatClass="2-" then factor=&StrokeRateM2mSDx2;
  if Gender="W" and BoatClass="1x" then factor=&StrokeRateW1xSDx2;
  if Gender="W" and BoatClass="2-" then factor=&StrokeRateW2mSDx2;
  a=a*factor;
  end;
CLpm=(Upper-Lower)/2;
drop StdErrPred tValue Probt;
format Estimate Lower Upper CLpm 5.&deceff DF 5.0;

proc sort;
by Effect BoatClass Gender Estimate;

data boatid;
set solr1;
if effect="Intercept";

title2 "Random-effect solution (&unitsrawlog)";
title3 "Intercept is boat indiv differences in mean efficiency";
*title4 "Warning: after adjusting for between-boat differences in mean &predboat";
proc print data=boatid noobs;
```

```
var Effect BoatClass Gender BoatID Estimate DF Alpha Lower Upper
    CLpm;
by Effect BoatClass Gender;
run;

title2 "Random-effect solution (&unitsrawlog)";
title3 "PowerPeach is relative differences in effect of 2 within-strokeset SD";
proc print data=solr1 noobs;
var Effect BoatClass Gender BoatID Estimate DF Alpha Lower Upper
    CLpm;
by Effect BoatClass Gender;
where Effect="PowerPeach";
run;

title3 "StrokeRate is relative differences in effect of 2 within-strokeset SD";
proc print data=solr1 noobs;
var Effect BoatClass Gender BoatID Estimate DF Alpha Lower Upper
    CLpm;
by Effect BoatClass Gender;
where Effect="StrokeRate";
run;

/*
data date;
set solr1;
if effect="Date";
drop BoatID StrokeSet;

title2 "Random-effect solution (&unitsrawlog)";
title3 "Date is mean differences between dates, e.g., due to changes in environment";
proc print data=date noobs;
var Effect BoatClass Gender Date Estimate DF Alpha Lower Upper
    CLpm;
by Effect BoatClass Gender;
run;
*/

data strokeset;
set solr1;
if effect="StrokeSet" and estimate ne 0; *with subjec=BoatID we get lots of zeros;
drop BoatID Date;

proc sort;
by BoatClass Gender StrokeSet;

proc sort data=decodeset;
by BoatClass Gender StrokeSet;

*proc print data=strokeset;run;
```

```
data strokeset1;
merge decodeset strokeset wind(drop=_freq_ _type_ HeadWindSD);
by BoatClass Gender StrokeSet;

title2 "Random-effect solution (&unitsrawlog)";
title3 "StrokeSet is boat mean differences between races within dates, e.g., due to
changes in environment";
proc print noobs data=strokeset1;
var Event BoatClass Gender StrokeSet BoatID Race Date Time HeadWindMean
Estimate Lower Upper CLpm Alpha;
format Estimate Lower Upper CLpm 5.&deceff HeadWindMean 5.1;
by BoatClass Gender;
run;

title2 "Predicted 2000-m time of boats at their mean power and stroke rate in each
race,";
title3 "plus multiples of 5% and 2.5% respectively";
data predict1;
set pred;
if &dep=.;
array a pred lower upper;
do over a;
  a=exp(a/100);
  end;
Predicted2000mTime=2000/pred;
UpperCL=2000/lower;
LowerCL=2000/upper;
CLpm=(UpperCL-LowerCL)/2;
if PowerExtraPC=0 and StrokeExtraPC=0 then
PredMinusActual=Predicted2000mTime-RaceTime;
array b HeadWindMean PowerPredictor StrokeRatePredictor RaceTime
Predicted2000mTime PredMinusActual LowerCL UpperCL CLpm;
do over b;
  b=round(b,0.1);
  end;
format RaceTime Predicted2000mTime LowerCL UpperCL CLpm 5.1;
*format Predicted2000mTime LowerCL UpperCL CLpm mmss8.1;
keep BoatClass Gender BoatID Race Event PowerExtraPC StrokeExtraPC
PredMinusActual
  PowerPredictor StrokeRatePredictor HeadWindMean RaceTime Predicted2000mTime
LowerCL UpperCL CLpm;

proc sort;
by BoatClass Gender BoatID Race Event;

proc print noobs;
var BoatClass Gender BoatID Race Event HeadWindMean PowerExtraPC
StrokeExtraPC
  PowerPredictor StrokeRatePredictor RaceTime Predicted2000mTime
PredMinusActual LowerCL UpperCL CLpm;
```

```
by BoatClass Gender BoatID Race Event;
run;

title3 "Simple stats for predicted minus actual race time";
title4 "Nobs is number of races";
proc means maxdec=1 data=predict1;
var PredMinusActual CLpm;
class BoatClass Gender;
where PowerExtraPC=0 and StrokeExtraPC=0;
run;

libname out1 xlsx '/folders/myshortcuts/ExternalFiles/Projects/_VU Melbourne/Ana
Holt/Study 3/Predicted 2000-m times.xlsx';
data out1.x;
set predict1;
run;
libname out1 clear;

*merge the random-effect solutions with the power2 dataset;
proc sort data=power2;
by BoatClass Gender BoatID;

proc sort data=boatid;
by BoatClass Gender BoatID;

data powerid;
set solr;
if effect="PowerPeach";
rename Estimate=PowerSlopeIndDiff;
keep estimate Boatclass Gender BoatID;
format estimate 6.2;

data strokerateid;
set solr;
if effect="StrokeRate";
rename Estimate=StrokeRateSlopeIndDiff;
keep estimate Boatclass Gender BoatID;
format estimate 6.2;
run;

data slopepower;
set est;
if label="PowerPeach /%";
rename estimate=PowerSlopeMean;
keep estimate Boatclass Gender;
format estimate 6.2;

data slopestrokerate;
set est;
if label="StrokeRate /%";
```

```
rename estimate=StrokeRateSlopeMean;
keep estimate Boatclass Gender;
format estimate 6.2;

data power2a;
merge power2 slopepower;
by BoatClass Gender;

data power2b;
merge power2a powerid;
by BoatClass Gender BoatID;

data power2c;
merge power2b slopestrokerate;
by BoatClass Gender;

data power2d;
merge power2c strokerateid;
by BoatClass Gender BoatID;
run;

*proc print data=power2d(obs=10);run;

data power3;
merge power2d boatid(keep= BoatClass Gender BoatID Estimate
rename=(Estimate=BoatEfficiency));
by BoatClass Gender BoatID;
if BoatID ne "WHHM1x"; *these two deletions appear to be redundant;
if BoatID="VKGVJHW2-" and Race="Rep" then delete;
if BoatClass="1x" and Gender="W" then BoatEfficiency=0; *had zero variance, yet
SAS gives it values;
run;
/*
title "to check for mismatch of boats";
proc print;
by BoatClass Gender;
run;
*/
proc sort;
by BoatClass Gender BoatID Event Race;

proc sort data=strokeset1;
by BoatClass Gender BoatID Event Race;

data power4;
merge power3 strokeset1(drop=df factor effect lower upper alpha clpm
rename=(Estimate=Environment));
by BoatClass Gender BoatID Event Race;
if BoatID ne "WHHM1x";
if BoatID="VKGVJHW2-" and Race="Rep" then delete;
```

```
/*
title "to check mismatch of races";
proc print;
by BoatClass Gender;
run;
*/
*merge in the residual SDs (Variability);
proc sort data=power4;
by BoatClass Gender StrokeSet;

proc sort data=resid;
by BoatClass Gender StrokeSet;

data power5;
merge power4(in=a) resid;
by BoatClass Gender StrokeSet;
if a;
run;

*get SD of BoatEfficiency and Environment from covall and merge with racepower
dataset;
data boateffsd;
set covall(keep=BoatClass Gender Covparm Estimate);
if covparm="Intercept";
BoatEffSD=100*log(1+Estimate/100);
drop Estimate Covparm;

data environsd;
set covall(keep=BoatClass Gender Covparm Estimate);
if covparm="StrokeSet";
EnvironSD=100*log(1+Estimate/100);
drop Estimate Covparm;
run;

data ss.racepower;
merge power5 boateffsd environsd;
by BoatClass Gender;
format HeadWindMean Variability BoatEffSD EnvironSD 5.1;
run;

proc sort;
by BoatClass Gender BoatID Date StrokeSet;

title "Final dataset for predicting race speed with mean power and random effects";
proc print;
by BoatClass Gender;
run;

*print to excel file;
```

```
libname out1 xlsx '/folders/myshortcuts/ExternalFiles/Projects/_VU Melbourne/Ana
Holt/Study 3/final dataset to predict speed.xlsx';
data out1.x;
set ss.racepower;
format StrokeTime RaceTime 5.1;
run;
libname out1 clear;
```

Appendix U: Study Three statistical analysis SAS script for multiple linear regression analyses

```
/*
This is a modified version of predict speed with power boatpred 23Apr20.sas
It uses ss.racepower, generated by create racepower sasset 13June20.sas  no, 30Sep20.
Here are the variables in ss.racepower:
  BoatClass Gender BoatID Event Race NoOfStrokes StrokeRate StrokeTime Category
RaceTime RaceOrder Year
  BoatPower StrokePower BowPower BoatEfficiency StrokeSet Date Time
Environment
  BoatEffSD EnvironSD
BoatEfficiency, Environment, BoatEffSD and EnvironSD are log transformed already.
Use this dataset with a modified version of predict speed with power boatpred
23Apr20.sas
See final dataset for predicting speed with power & rand effects.html for the dataset.
*/
libname ss '/folders/myshortcuts/ExternalFiles/Projects/_VU Melbourne/Ana
Holt/Study 3';

%let alpha=0.1;
%let decdep=1;
%let deceff=1;
%let nob=;
%let convcrit=CONVH=1E-8 convf=1E-8;
%let StdzedMagniThresh=0.20; *smallest stdized beneficial change;
%let MagniThresh=0.3; *smallest beneficial change;
%let parms=;
*let title1=;
%let subset=if StrokeNo>10;

%let dep=BoatSpeed;
%let logflag=1;

*%let predboat=BoatEfficiency;
*%let logflagpred=0;
*%let decpredboat=1;
%let nob=;
%let parms=;
%let type=type=un;

data dat1;
set ss.racepower;
BoatSpeed=2000/RaceTime;
run;

*proc print data=ss.study3(obs=100);
run;

data _null_;
```

```
if &logflag then call symput('unitsrawlog',"percent");
else call symput('unitsrawlog',"raw");
run;

title "Number of races for each boat in this analysis";
proc sort data=dat1;
by BoatClass Gender BoatID;

proc freq data=dat1;
tables BoatID/nocum nopercent;
by BoatClass Gender;
run;

title "Simple stats for BoatSpeed (m/s)";
title2 "N is the number of stroke sets";
proc means maxdec=2 data=dat1 nonobs;
var BoatSpeed;
class BoatClass Gender;
run;

title "Simple stats for BoatPower (W)";
title2 "N is the number of stroke sets";
proc means maxdec=0 data=dat1 nonobs;
var BoatPower;
class BoatClass Gender;
run;

title "Simple stats for StrokeRate (spm)";
title2 "N is the number of stroke sets";
proc means maxdec=1 data=dat1 nonobs;
var StrokeRate;
class BoatClass Gender;
run;

title "Simple stats for HeadWindMean (m/s)";
title2 "N is the number of stroke sets";
proc means maxdec=1 data=dat1 nonobs;
var HeadWindMean;
class BoatClass Gender;
run;

data dat5;
set dat1;
if &logflag then do;
  &dep=100*log(&dep);
  BoatPower=100*log(BoatPower);
  StrokeRate=100*log(StrokeRate);
  end;
*if &logflagpred then &predboat=100*log(&predboat);
run;
```

```
*proc print data=dat3(obs=1000);
run;

title "Simple stats for log-transformed BoatSpeed";
title2 "N Obs is the number of stroke sets";
proc means nonobs maxdec=1 data=dat5;
var BoatSpeed;
class BoatClass Gender;
run;

title "Simple stats for log-transformed BoatPower and StrokeRate and Variability";
title2 "N Obs is the number of stroke sets";
proc means nonobs maxdec=1 data=dat5;
var BoatPower StrokeRate Variability;
class BoatClass Gender;
run;

title "Back-transformed values of SD and 2SD (%) used for effect of BoatPower and
StrokeRate and Variability";
title2 "N is the number of stroke sets";
proc means noprint data=dat5;
var BoatPower StrokeRate Variability;
by BoatClass Gender;
output out=powersd std=BoatPowerSD StrokeRateSD VariabilitySD n=N;

data powersd1;
set powerSD;
BoatPower2SD=2*BoatPowerSD;
StrokeRate2SD=2*StrokeRateSD;
Variability2SD=2*VariabilitySD;
array a BoatPowerSD BoatPower2SD StrokeRateSD StrokeRate2SD VariabilitySD
Variability2SD;
do over a;
  a=100*exp(a/100)-100;
  end;
format BoatPowerSD BoatPower2SD StrokeRateSD StrokeRate2SD VariabilitySD
Variability2SD 5.1;

proc print nooobs;
var BoatClass Gender N BoatPowerSD BoatPower2SD StrokeRateSD StrokeRate2SD
VariabilitySD Variability2SD;
run;

proc means noprint data=dat5;
var BoatEfficiency;
by BoatClass Gender BoatID;
output out=boatmean mean=;

title "Between-boat simple stats for BoatEfficiency (already log-transformed)";
```

```
title2 "N Obs is the number of boats";
proc means nonobs maxdec=1 data=boatmean;
var BoatEfficiency;
class BoatClass Gender;
run;

title "Simple stats for Environment (already log-transformed)";
title2 "N Obs is the number of stroke sets";
proc means nonobs maxdec=1 data=dat5;
var Environment;
class BoatClass Gender;
run;


title "Back-transformed values of SD and 2SD (%) used for effects of BoatEfficiency
and Environment";
title2 "These came from the covparms in create racepower sasset 5Oct20.sas";
proc means noprint data=dat5;
var BoatEffSD EnvironSD;
by BoatClass Gender;
output out=sd mean=;

data sd1;
set sd;
BoatEff2SD=2*BoatEffSD;
Environ2SD=2*EnvironSD;
array a BoatEffSD BoatEff2SD EnvironSD Environ2SD;
do over a;
  a=100*exp(a/100)-100;
  end;
format _numeric_ 5.1;

proc print noobs;
var BoatClass Gender BoatEffSD BoatEff2SD EnvironSD Environ2SD;
run;

data dat6;
set dat5;
BoatEfficiency=BoatEfficiency/2/BoatEffSD;
if BoatClass="1x" and Gender="W" then BoatEfficiency=0; *zero variance for BoatID
in the stroke-by-stroke analysis;
Environment=Environment/2/EnvironSD;
run;

proc standard data=dat6 out=dat7 std=0.5 mean=0;
var BoatPower StrokeRate Variability;
by BoatClass Gender;
run;

proc standard data=dat5 out=dat5a mean=0;
```

```
var BoatPower StrokeRate;
by BoatClass Gender;
run;

data cov lsm lsmdiff lsmdiff1 lsmdiff2  lsmest est solf solr pred pred1;

%let convcrit=CONVH=1E-8 convf=1E-8;

title1 "&dep predicted by Headwind BoatPower StrokeRate BoatEfficiency
Environment & Variability in a log-log regression";ods select none;
*ods listing close;
proc mixed data=dat5a covtest cl alpha=&alpha &nob &convcrit;
*class BoatID Race StrokeSet Date;
*model &dep=BoatPower BoatEfficiency Environment/outp=pred s residual ddfm=sat
alphap=&alpha ddfm=sat; *better without ddfm=sat?;
model &dep=BoatPower StrokeRate BoatEfficiency HeadWindMean Environment
Variability/outp=pred s residual ddfm=sat alphap=&alpha ddfm=sat; *better without
ddfm=sat?;
estimate "Intercept" int 1/cl alpha=&alpha;
estimate "BoatPower /%" BoatPower 1/cl alpha=&alpha;
estimate "StrokeRate /%" StrokeRate 1/cl alpha=&alpha;
estimate "BoatEfficiency /%" BoatEfficiency 1/cl alpha=&alpha;
estimate "HeadWindMean /(1m/s)" HeadWindMean 1/cl alpha=&alpha;
estimate "HeadWindMean /(2m/s)" HeadWindMean 2/cl alpha=&alpha;
estimate "Environment /%" Environment 1/cl alpha=&alpha;
estimate "Variability /%" Variability 1/cl alpha=&alpha;
*no random effects other than the residual;
/*
lsmestimate Device*SerialNumber "NK-Vicon:" 0;
lsmestimate Device*SerialNumber
  "Unit 1100827" 1 0 0 0  0 0 0  0 0 0  -1 0 0 0,
  "Unit 1101134" 0 1 0 0  0 0 0  0 0 0  0 -1 0 0,
  "Unit 1101819" 0 0 1 0  0 0 0  0 0 0  0 0 -1 0,
  "Unit 1101823" 0 0 0 1  0 0 0  0 0 0  0 0 0 -1
  /cl alpha=0.1;
*/
ods output classlevels=clev;
ods output covparms=cov;
*ods output lsmeans=lsm;
*ods output diffs=lsmdiff;
ods output estimates=est;
*ods output solutionf=solf;
*ods output solutionr=solr;
*ods output lsmestimates=lsmest;
by BoatClass Gender;
run;
ods select all;

/*
proc sort data=pred1;
```

```
by BoatClass Gender StrokeSet;
*/
/*
ods graphics / reset width=12cm height=10cm imagemap attrpriority=none;
proc sgplot data=pred1; *uniform=all;
scatter x=pred y=Resid/markerattrs=(size=8 color=black symbol=circlefilled)
filledoutlinedmarkers MARKERFILLATTRS=(color=black);
*scatter x=StrokeNo y=Resid/markerattrs=(size=3 color=black symbol=circlefilled)
filledoutlinedmarkers MARKERFILLATTRS=(color=black);
refline 0/axis=y lineattrs=(pattern=dot thickness=1 color=blue);
by BoatClass Gender;
*where Gender="M" and BoatClass="2-" and StrokeSet=36;
run;
ods graphics / reset;
*/

data pred1;
set pred;
/*
if &logflag then do;
  *&pred=exp(&pred/100);
  &dep=exp(&dep/100);
  pred=exp(pred/100);
  end;
*/

*proc print data=pred;run;

*title2 "Raw residuals vs predicteds";
title2 "Standardized residuals vs predicteds";
options ls=80 ps=36;
proc plot data=pred1 ;
plot StudentResid*pred/vref=0;
by BoatClass Gender;
run;

data pred2;
set pred1;
if abs(StudentResid)>3.5;

proc print data=pred2;
*var BoatClass Gender BoatID Date Race StrokeSet StrokeNo &dep pred resid
Studentresid;
title2 "Outliers (Standardized residual >3.5)";
format &dep 5.&decdep studentresid 5.1;
by BoatClass Gender;
run;

data est1;
set est;
```

```
if estimate=0 then estimate=.;
array a estimate lower upper;
if &logflag=1 and Label ne "Intercept" then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(upper-lower)/2;
*if index(Label,"RFDAv") and index(Label,BoatClass)=0 then delete;

title2 "Fixed effects (&unitsrawlog)";
title3 "Ignore the intercept; BoatPower and StrokeRate are the indics in
BoatSpeed=k.BoatPower^x.SR^y";
title4 "BoatEfficiency and Environment are expected to have coefficients of 1.00";
proc print data=est1 noobs;
var BoatClass Gender label Estimate CLpm Lower Upper DF alpha;
format estimate CLpm lower upper 5.2;
by BoatClass Gender;
run;

data cov lsm lsmdiff lsmdiff1 lsmdiff2  lsmest est solf solr pred pred1;

%let convcrit=CONVH=1E-8 convf=1E-8;

title1 "&dep predicted by Headwind and 2SD BoatPower StrokeRate BoatEfficiency
Environment & Variability in a log-log regression";
ods select none;
*ods listing close;
proc mixed data=dat7 covtest cl alpha=&alpha &nob &convcrit;
*class BoatID Race StrokeSet Date;
*model &dep=BoatPower BoatEfficiency Environment /outp=pred s residual ddfm=sat
alphap=&alpha ddfm=sat; *better without ddfm=sat?;
model &dep=BoatPower StrokeRate BoatEfficiency HeadWindMean Environment
Variability/outp=pred s residual ddfm=sat alphap=&alpha ddfm=sat; *better without
ddfm=sat?;
estimate "Intercept" int 1/cl alpha=&alpha;
estimate "BoatPower /2SD" BoatPower 1/cl alpha=&alpha;
estimate "StrokeRate /2SD" StrokeRate 1/cl alpha=&alpha;
estimate "BoatEfficiency /2SD" BoatEfficiency 1/cl alpha=&alpha;
estimate "HeadWindMean /(1m/s)" HeadWindMean 1/cl alpha=&alpha;
estimate "HeadWindMean /(2m/s)" HeadWindMean 2/cl alpha=&alpha;
estimate "Environment /2SD" Environment 1/cl alpha=&alpha;
estimate "Variability /2SD" Variability 1/cl alpha=&alpha;
*no random effects other than the residual;
/*
lsmestimate Device*SerialNumber "NK-Vicon:" 0;
lsmestimate Device*SerialNumber
  "Unit 1100827" 1 0 0 0  0 0 0  0 0 0  -1 0 0 0,
  "Unit 1101134" 0 1 0 0  0 0 0  0 0 0  0 -1 0 0,
  "Unit 1101819" 0 0 1 0  0 0 0  0 0 0  0 0 -1 0,
  "Unit 1101823" 0 0 0 1  0 0 0  0 0 0  0 0 0 -1
  /cl alpha=0.1;
```

```
*/
ods output classlevels=clev;
ods output covparms=cov;
*ods output lsmeans=lsm;
*ods output diffs=lsmdiff;
ods output estimates=est;
*ods output solutionf=solf;
*ods output solutionr=solr;
*ods output lsmestimates=lsmest;
by BoatClass Gender;
run;
ods select all;

*title2 "Random effects, to check on adequacy of the model";
*proc print data=cov noobs;
*by BoatClass Gender;
run;

*proc print data=clev;run;
*proc print data=cov;run;
*proc print data=est;
*by BoatClass Gender;
run;

data est1;
set est;
if estimate=0 then estimate=.;
if Label ne "Intercept";
array a estimate lower upper;
if &logflag=1 then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(upper-lower)/2;
*if index(Label,"RFDAv") and index(Label,BoatClass)=0 then delete;

title2 "Fixed effects (&unitsrawlog)";
title3 "Note that the estimates are now for 2SD of the predictor (and still for 1 and 2 m/s
for HeadWindMean)";
proc print data=est1 noobs;
var BoatClass Gender label Estimate CLpm Lower Upper DF alpha;
format estimate CLpm lower upper 5.1;
by BoatClass Gender;
run;

*thresholds via given smallest important;
data thresholds;
*set stdsd;
Units="Raw";
if &logflag then Units="%";
magnithresh=&MagniThresh;
```

```
if &logflag=0 then do; *these raw thresholds are actually via standardization;
Threshold="small   "; DeltaMeanBene=magnithresh; DeltaMeanHarm=-magnithresh;
SDthreshold=abs(magnithresh)/2; output;
  Threshold="moderate"; DeltaMeanBene=magnithresh*3; DeltaMeanHarm=-
magnithresh*3; SDthreshold=abs(DeltaMeanBene)/2; output;
  Threshold="large"; DeltaMeanBene=magnithresh*6; DeltaMeanHarm=-
magnithresh*6; SDthreshold=abs(DeltaMeanBene)/2; output;
  Threshold="vlarge"; DeltaMeanBene=magnithresh*10; DeltaMeanHarm=-
magnithresh*10; SDthreshold=abs(DeltaMeanBene)/2; output;
  Threshold="xlarge"; DeltaMeanBene=magnithresh*20; DeltaMeanHarm=-
magnithresh*20; SDthreshold=abs(DeltaMeanBene)/2; output;
  end;
else do;
  magnithresh=100*log(1+magnithresh/100);
  Threshold="small   "; DeltaMeanBene=100*exp(magnithresh/100)-100;
DeltaMeanHarm=100*exp(-magnithresh/100)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2)-100; output;
  Threshold="moderate"; DeltaMeanBene=100*exp(magnithresh/100*3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*3)-100; output;
  Threshold="large"; DeltaMeanBene=100*exp(magnithresh/100*1.6/0.3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*1.6/0.3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*1.6/0.3)-100; output;
  Threshold="vlarge"; DeltaMeanBene=100*exp(magnithresh/100*2.5/0.3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*2.5/0.3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*2.5/0.3)-100; output;
  Threshold="xlarge"; DeltaMeanBene=100*exp(magnithresh/100*4.0/0.3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*4.0/0.3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*4.0/0.3)-100; output;
  end;

title2 "&dep magnitude thresholds (&unitsrawlog), based on a given smallest important
for means of &magnithresh (&unitsrawlog).";
title3 "Factors for the thresholds for moderate, large, v.large and x.large are .9/.3x,
1.6/.3x, 2.5/.3x and 4/.3x the smallest important,";
title4 "i.e., competitive athlete thresholds; thresholds for SDs are half those for means.";
proc print noobs;
var Threshold Units DeltaMeanBene DeltaMeanHarm SDthreshold;
format DeltaMeanBene DeltaMeanHarm SDthreshold 5.&decdep;format
DeltaMeanBene DeltaMeanHarm SDthreshold 5.&decdep;
where &logflag=0;
run;

proc print noobs;
var Threshold Units DeltaMeanBene DeltaMeanHarm SDthreshold;
format DeltaMeanBene DeltaMeanHarm 5.&deceff SDthreshold 5.2;
where &logflag=1;
run;

*make macro variables for magnitude thresholds for the MBD steps;
```

```
data _null_;
length ThreshX $ 9;
set thresholds;
if &logflag then Thresh=abs(100*log(1+DeltaMeanBene/100)); *convert back to log
value, could do it with DeltaMeanHarm;
else Thresh=abs(DeltaMeanBene);
ThreshX=trim(Threshold)||'X';
call symput(ThreshX,Thresh);
run;
/*
data check;
Smallvalue=&smallx;
Modvalue=&moderatex;

proc print;run;
*/

title2 "MBD for fixed effects with a given smallest important for means of
&magnithresh (&unitsrawlog)";
data est1;
set est;
if index(Label,"2SD");
length Prob $ 8 Magni $ 4 QualMag $ 8;
QualMag="Trivial";
if abs(estimate)>&smallx then QualMag="Small";
if abs(estimate)>&moderatex then QualMag="Moderate";
if abs(estimate)>&largex then QualMag="Large";
if abs(estimate)>&vlargex then QualMag="Vlarge";
if abs(estimate)>&xlargex then QualMag="Xlarge";
MagniThresh=&MagniThresh;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh))/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh))/StdErr,DF);
if &LogFlag=1 then do;
  if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  else do;
    ChancePos=100*(1-ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  end;

ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
ClinFlag=1; *want inferences to be clinical;
*if index(label,"2SD") then ClinFlag=0; *covariates definitely need to be non-clinical;
*clinical inferences;
if clinflag then do;
```

```
Precision="unclear";
ChPos=ChancePos; ChNeg=ChanceNeg;
if MagniThresh<0 then do;
  ChPos=ChanceNeg; ChNeg=ChancePos;
  end;
if ChNeg<0.5 then do;
  Precision="@25/.5%";
  if ChNeg<0.1 then Precision="@5/.1% ";
  Magni="bene";
  if ChNeg<0.1 and ChPos>5 then Prob="unlikely";
  if ChPos>25 then Prob="possibly";
  if ChPos>75 then Prob="likely  ";
  if ChPos>95 then Prob="v.likely";
  if ChPos>99.5 then Prob="m.likely";
  if ChPos<25 and prob ne "unlikely" then do;
    Magni="triv";
    if ChanceTriv>25 then Prob="possibly";
    if ChanceTriv>75 then Prob="likely  ";
    if ChanceTriv>95 then Prob="v.likely";
    if ChanceTriv>99.5 then Prob="m.likely";
    end;
  end;
else do; *ChNeg>0.5;
  if ChPos<25 then do;
    Precision="@25/.5%";
    if ChPos<5 then Precision="@5/.1% ";
    if ChanceTriv>25 then do;
      Magni="triv";Prob="possibly";
      if ChanceTriv>75 then Prob="likely";
      if ChanceTriv>95 then Prob="v.likely";
      if ChanceTriv>99.5 then Prob="m.likely";
      end;
    if ChNeg>25 then do;
      Magni="harm";Prob="possibly";
      if ChNeg>75 then Prob="likely  ";
      if ChNeg>75 then Prob="likely  ";
      if ChNeg>95 then Prob="v.likely";
      if ChNeg>99.5 then Prob="m.likely";
      end;
    end;
  end;
if Precision="unclear" and
  (MagniThresh>0 and ORPosNeg>25/75/(0.5/99.5) or StdzedMagniThresh<0 and
ORNegPos>25/75/(0.5/99.5))
  then do;
  Precision="OR>66.3";
  Magni="bene";
  if ChPos>25 then Prob="possibly";
  if ChPos>75 then Prob="likely  ";
  if ChPos>95 then Prob="v.likely";
```

```
  if ChPos>99.5 then Prob="m.likely";
  end;
output;
end;
*mechanistic inferences;
ClinFlag=0;
Precision="unclear";
Prob="";
Magni="     ";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then Precision="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then Precision="@99%  ";
if Precision ne "unclear" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if Precision ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
*end;
output;

data est2;
set est1;
if estimate=0 or estimate=. then do;
  estimate=.; magnithresh=.; magni=""; Precision=""; Prob=""; Units=""; Magni="";
Precision=.; QualMag="";
  end;
array a estimate lower upper;
if &logflag then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(Upper-lower)/2;
rename df=DegFree;
if index(Label,".")=1 then Label=substr(Label,2);
run;

*options ls=135 ps=80;
title3 "Units for estimates, confidence limits and smallest important are &unitsrawlog";
title4 "Non-clinical inferences";
proc print data=est2 noobs;
where clinflag=0;
```

```
var BoatClass Gender label estimate CLpm lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos QualMag Prob Magni Precision;
format estimate CLpm lower upper MagniThresh 5.1 Probt best5. ChanceNeg
ChanceTriv
  ChancePos 5.1 DegFree 5.0;
by BoatClass Gender;
run;

data covall;
*length Device $ 5 Group $ 12;
set cov;
if covparm ne "UN(2,1)";
alpha=&alpha;
DegFree=2*ZValue**2;
*if Lower=. then do;
  *Lower=DegFree*estimate/CINV(1-alpha/2,DegFree);
  *Upper=DegFree*estimate/CINV(alpha/2,DegFree);
  *conf limits via normal dist;
if StdErr ne 0 then do;
  lower=estimate+probit(alpha/2)*StdErr;
  upper=estimate-probit(alpha/2)*StdErr;
  end;
array a estimate lower upper;
do over a;
  a=sign(a)*sqrt(abs(a));
  end;
if &logflag=1 then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(upper-lower)/2;
*if substr(covparm,1,2) ne "UN" then CLpm=(upper-lower)/2;
CLtd=sqrt(upper/lower);
drop StdErr--ProbZ;
*if covparm="UN(1,1)" then covparm="Intercept";
*if covparm="UN(2,2)" then covparm="PowerPeach";
*Group=substr(Group,8);

title2 "Random effects as standard deviations (&unitsrawlog)";
title3 "Residual is the unexplained differences in speed between races";
proc print noobs data=covall;
var BoatClass Gender covparm estimate CLpm lower upper alpha;
format estimate lower upper CLpm 5.&deceff CLtd 5.2 DegFree 5.0;
*by BoatClass Gender;
run;
/*
proc print noobs data=covall;
var BoatClass Gender covparm subject Group estimate CLpm lower upper alpha;
format estimate lower upper CLpm 5.2 CLtd 5.2 DegFree 5.0;
*by BoatClass Gender;
where covparm="PowerPeach";
```

```
run;
*/

title2 "Non-clinical MBD for random effects";
title3 "Magnithresh is half the given smallest difference of &magnithresh
(&unitsrawlog) for means";
title4 "&predboat is boat indiv differences in slope";
*title6 "Non-clinical MBD for SD representing random effects";
*title3 "Intercept is boat indiv differences in mean efficiency";
*title4 "StrokeSet is boat mean differences between races, e.g., due to changes in
environment";
*title5 "Date is mean differences between dates, e.g., due to changes in environment";
*title6 "Residual is the stroke to stroke variation in speed";
data cov1;
set cov;
QualMag="Trivial ";
if sqrt(abs(estimate))>&smallx/2 then QualMag="Small";
if sqrt(abs(estimate))>&moderatex/2 then QualMag="Moderate";
if sqrt(abs(estimate))>&largex/2 then QualMag="Large";
if sqrt(abs(estimate))>&vlargex/2 then QualMag="Vlarge";
if sqrt(abs(estimate))>&xlargex/2 then QualMag="Xlarge";
*if substr(Group,8)="NK" or substr(Group,8)="Peach"; *add or modify, depending on
the analysis;
*lower=estimate+probit(alpha/2)*StdErr; *for those models where nobound did not
work;
*upper=estimate-probit(alpha/2)*StdErr;
DF=999;
MagniThresh=abs(&MagniThresh)/2;
if &logflag then Magnithresh=100*exp(log(1+abs(&magnithresh)/100)/2)-100;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh)**2)/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh)**2)/StdErr,DF);
if &logflag then do;
  *if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-
(100*log(1+MagniThresh/100))**2)/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+(100*log(1+MagniThresh/100))**2)/StdErr,DF);
    end;
ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
*ClinFlag=0; *want all inferences to be non-clinical for within-subject random effect;
*mechanistic inferences;
Precision="unclear";
Prob="       ";
Magni="    ";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then Precision="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then Precision="@99%  ";
if Precision ne "unclear" then do;
  Magni="+ive ";
```

```
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if Precision ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
if not stderr then do; Magni="";Precision=""; end;
Group=substr(Group,8);

data cov2;
set cov1;
alpha=&alpha;
*if covparm ne "Residual" then do;
  lower=estimate+probit(alpha/2)*StdErr;
  upper=estimate-probit(alpha/2)*StdErr;
*  end;
array a estimate lower upper;
do over a;
  a=sign(a)*sqrt(abs(a));
  end;
DegFree=2*Zvalue**2;
array r SD lower upper;
if &logflag=1 then do over r;
  r=100*exp(r/100)-100;
  end;
CLpm=(upper-lower)/2;
*if substr(covparm,1,2) ne "UN" then CLpm=(upper-lower)/2;
CLtd=sqrt(upper/lower);
run;

title6 "Non-clinical MBD for SD representing random effects";
title3 "Residual is the unexplained differences in speed between races";
proc print data=cov2 noobs;
var BoatClass Gender covparm estimate CLpm lower upper alpha
  MagniThresh ChanceNeg ChanceTriv ChancePos QualMag Prob Magni Precision;
format estimate CLpm lower upper 5.2 MagniThresh 5.2 ChanceNeg ChanceTriv
  ChancePos 5.1 DF 5.0;
*by BoatClass Gender;
run;
```

Appendix V: Study Four statistical analysis SAS script for boat predictors (one predictor measure per crew)

```
*libname ss '/folders/myshortcuts/ExternalFiles/Projects/_VU Melbourne/Ana
Holt/Study 3';
libname ss '/folders/myshortcuts/PhD/Study 3_Technical Determinants/Raw data';
*StrokeRate is now a predictor, along with PowerPeach;

*VBCaM2-     VBCaVMHM2-        M        2-        Heat;

data dat1;
set ss.study3;
attrib _character_ _numeric_ label="";
run;

*proc print data=ss.study3(obs=100);
run;

%macro anaboat;
data _null_;
if &logflag then call symput('unitsrawlog',"percent");
else call symput('unitsrawlog',"raw");
run;

/*
proc sort data=dat1;
by Gender Participant Race;

ods graphics / reset width=20cm height=16cm imagemap attrpriority=none;
title "Scatterplot of &dep vs StrokeNo";
proc sgplot data=dat1 uniform=scale;
styleattrs
  datacolors=(black blue red pink greenyellow)
  datalinepatterns=(dot)
  datacontrastcolors=(black blue red pink greenyellow)
  datasymbols=(circlefilled);
  *datasymbols=(circlefilled squarefilled diamondfilled trianglefilled);
*reg x=Vicon y=&dep/nomarkers name='def' group=DeviceUnit;
*reg x=Vicon1 y=Identity/nomarkers name='def' lineattrs=(color=black pattern=dash
thickness=0.5);
scatter x=StrokeNo y=&dep/markerattrs=(size=5) filledoutlinedmarkers name='abc'
group=Race;
*scatter x=StrokeNo y=&dep/groupdisplay=cluster clusterwidth=0.3
markerattrs=(size=8) filledoutlinedmarkers group=DeviceUnit  name='abc';
*series x=&dep y=MeanLine /lineattrs=(pattern=dash thickness=1 color=black);
*keylegend 'def' /noborder titleattrs=(size=16) valueattrs=(size=16);
keylegend 'abc' /title="Race:" noborder titleattrs=(size=16) valueattrs=(size=16);
yaxis label="&dep" labelpos=top labelattrs=(size=16) valueattrs=(size=16);
xaxis label="StrokeNo" labelattrs=(size=16) valueattrs=(size=16);
refline 10/axis=x lineattrs=(pattern=dot thickness=1 color=black);
```

```
*refline MeanDep/axis=x lineattrs=(pattern=dash thickness=0.25 color=black);
by Gender Participant;
*where Participant="VMTW2-";
where StrokeNo>3; * and  Participant="VMTW2-";
run;
ods graphics/reset;
*/
proc sort data=dat1;
by Date Time BoatID ;

data dat2;
retain StrokeSet 0;
set dat1;
if lag(Date) ne Date or lag(Time) ne Time or lag(BoatID) ne BoatID then
StrokeSet=StrokeSet+1;
&subset;
/*
if &logflag=1 then &dep=100*log(&dep);
if &logflagpred=1 then &pred=100*log(&pred);
*/
if BoatID="VBCaVMHM2-" and Race="Heat" then delete;
run;

proc sort data=dat2;
by BoatClass Gender BoatID StrokeSet StrokeNo;
run;

*new 10Apr: get PowerPeach on the stern side minus on the bow side;
data oar1;
set dat2;
if Oar="1";
keep BoatClass Gender BoatID StrokeSet StrokeNo Participant PowerPeach;
rename PowerPeach=PowerOar1 Participant=RowerOar1;

data oar2;
set dat2;
if Oar="2";
keep BoatClass Gender BoatID StrokeSet StrokeNo Participant PowerPeach;
rename PowerPeach=PowerOar2 Participant=RowerOar2;

data bow;
set dat2;
if Side="B";
keep Time &predboat StrokeRate BoatClass Gender Race BoatID Date Participant
StrokeSet StrokeNo StrokeDuration PowerPeach AvBoatVel CatchSlipPeach;
rename Time=TimeB Participant=RowerBow PowerPeach=PowerPeachBow
CatchSlipPeach=CatchSlipBow;

data stroke;
set dat2;
```

```
if Side="S";
keep Time BoatClass Gender Race BoatID Participant StrokeSet StrokeNo PowerPeach
CatchSlipPeach WindDirectionDec WindAve;
rename Time=TimeS Participant=RowerStroke PowerPeach=PowerPeachStroke
CatchSlipPeach=CatchSlipStroke;

data dat4;
merge bow(in=a) stroke(in=b) oar1 oar2;
by BoatClass Gender BoatID StrokeSet StrokeNo;
if a and not b or b and not a then delete; *only 10 obs, plus VRMLM1x for one race;
PowerPeach=PowerPeachBow+PowerPeachStroke;
Power2minus1=PowerOar2-PowerOar1; *not used in this program;
Time=TimeB;
if TimeB="" then Time=TimeS;
drop TimeB TimeS;
if Race="Trials" then Race="Final";
if Race="Rep" or Race="Semi" then Race="Heat";
*if BoatID="AHHLM1x" or  BoatID="ANKLM1x" or  BoatID="SOMLM1x" or
BoatID="VACM1x" or  BoatID="VENM1x";
*if Gender="W" and BoatClass="2-";


data decodeset;
set dat4;
if lag(StrokeSet) ne StrokeSet;
keep BoatClass Gender StrokeSet Date Time Race BoatID;
run;

*proc print data=bow(obs=100);run;
/*
proc sort data=dat1;
by BoatClass Gender Participant Side;

data decodeside;
set dat1;
if lag(BoatID) ne BoatID or lag(Side) ne Side;
keep BoatClass Gender BoatID Side Participant;

*proc print noobs;
run;
*/

title "Within-boat simple stats for AvBoatVel (m/s)";
title2 "Nobs is the number of stroke sets";
proc means noprint data=dat4;
var AvBoatVel;
by BoatClass Gender BoatID StrokeSet;
*where Side="B";
output out=meansd mean=WthnBoatMean std=WthnBoatSD;
```

```
proc means maxdec=2;
var WthnBoatMean WthnBoatSD;
class BoatClass Gender;
run;

title "Within-boat simple stats for PowerPeach (W)";
title2 "Nobs is the number of stroke sets";
proc means noprint data=dat4;
var PowerPeach;
by BoatClass Gender BoatID StrokeSet;
*where Side="B";
output out=meansd mean=WthnBoatMean std=WthnBoatSD;

proc means maxdec=0;
var WthnBoatMean WthnBoatSD;
class BoatClass Gender;
run;

title "Within-boat simple stats for StrokeRate (spm)";
title2 "Nobs is the number of stroke sets";
proc means noprint data=dat4;
var StrokeRate;
by BoatClass Gender BoatID StrokeSet;
*where Side="B";
output out=meansd mean=WthnBoatMean std=WthnBoatSD;

proc means maxdec=1;
var WthnBoatMean WthnBoatSD;
class BoatClass Gender;
run;

data dat5;
set dat4;
PowerCubRoot=PowerPeach**(1/3);
if &logflag then do;
  &dep=100*log(&dep);
  PowerPeach=100*log(PowerPeach);
  PowerCubRoot=100*log(PowerCubRoot);
  StrokeRate=100*log(StrokeRate);
  end;
if &logflagpred then &predboat=100*log(&predboat);
run;

*proc print data=dat3(obs=1000);
run;

title "Within-boat simple stats for log-transformed AvBoatVel";
title2 "Nobs is the number of stroke sets";
proc means noprint data=dat5;
var AvBoatVel;
```

```
by BoatClass Gender BoatID StrokeSet;
*where Side="B";
output out=meansd mean=WthnBoatMean std=WthnBoatSD;

proc means maxdec=1;
var WthnBoatMean WthnBoatSD;
class BoatClass Gender;
run;

title "Within-boat simple stats for log-transformed PowerPeach";
title2 "Nobs is the number of stroke sets";
proc means noprint data=dat5;
var PowerPeach;
by BoatClass Gender BoatID StrokeSet;
*where Side="B";
output out=meansd mean=WthnBoatMean std=WthnBoatSD;

proc means maxdec=1;
var WthnBoatMean WthnBoatSD;
class BoatClass Gender;
run;

title "Between- and within-boat simple stats for raw &predboat";
title2 "Nobs is the number of boats";
proc means noprint data=dat4;
var &predboat;
by BoatClass Gender BoatID;
*where Side="B";
output out=predboatmean mean=&predboat.Mean std=WthnBoatSD;

data predboatmean1;
set predboatmean;
&predboat.MeanResc=&predboat.Mean;

proc standard data=predboatmean1 out=predboatmean2 mean=0 std=0.5;
var &predboat.MeanResc;
by BoatClass Gender;

proc means maxdec=&decpredboat;
var &predboat.Mean &predboat.MeanResc WthnBoatSD;
class BoatClass Gender;
run;

title "Between- and within-boat simple stats for log-transformed &predboat";
title2 "Nobs is the number of boats";
proc means noprint data=dat5;
var &predboat &dep PowerPeach;
by BoatClass Gender BoatID;
*where Side="B";
```

```
output out=predboatmean mean=&predboat.Mean &dep.Mean PowerPeachMean
std=WthnBoatSD;

data predboatmean1;
set predboatmean;
&predboat.MeanResc=&predboat.Mean;

proc standard data=predboatmean1 out=predboatmean2 mean=0 std=0.5;
var &predboat.MeanResc;
by BoatClass Gender;

proc means maxdec=&decpredboat;
var &predboat.Mean &predboat.MeanResc WthnBoatSD;
class BoatClass Gender;
where &logflagpred=1;
run;

title "Between-boat simple stats for log-transformed &dep.Mean and
PowerPeachMean";
title2 "Compare the SDs: we expect SD for PowerPeach to be more than 3x the SD for
AvBoatVel";
title3 "N is the number of boats";
proc means maxdec=1 data=predboatmean n mean std min max;
var &dep.Mean PowerPeachMean;
class BoatClass Gender;
run;

data dat6;
merge dat5 predboatmean2(keep=BoatClass Gender BoatID &predboat.Mean
&predboat.MeanResc);
by BoatClass Gender BoatID;
run;

/*
title "Within-boat correlations";
ods select none;
proc corr data=dat5 nosimple outp=corrs;
var AvBoatVel PowerPeach &predboat;
by BoatClass Gender BoatID StrokeSet;
*ods output FisherPearsonCorr=fish;
run;
ods select all;

*proc print data=corrs(obs=20);run;

data corrs1;
retain SortOrder;
set corrs;
if _Type_="CORR";
drop _type_ ;
```

```
if _name_ ne "";
if _name_="AvBoatVel" then SortOrder=0;
if lag(_name_) ne _name_ then SortOrder=SortOrder+1;
rename _name_=Predictor;
array a AvBoatVel PowerPeach &predboat;
do over a;
  if a=1 then a=.;
  end;

proc sort;
by BoatClass Gender SortOrder Predictor;

proc means noprint;
var AvBoatVel PowerPeach &predboat;
by BoatClass Gender SortOrder Predictor;
output out=corrs2 mean=;
run;

proc print noobs;
var BoatClass Gender Predictor AvBoatVel PowerPeach &predboat;
by BoatClass Gender;
format _numeric_ 5.2;
run;
*/
/*
proc freq data=dat4;
tables Participant*Race/nocol norow nopercent nocum;
by BoatClass Gender;
run
*/
/*
proc print data=dat3; *(obs=10);
where BoatID ne "VRMLM1x";
run;
*/
/*
data pdata;
Gender="M"; BoatClass="1x";
estimate=6;output;estimate=2;output; output;
estimate=9;output;estimate=5;output;estimate=10;output;estimate=6;output;
do i=1 to 6;
  estimate=5;
  output;
  end;
Gender="M"; BoatClass="2-";
do i=1 to 7;
  estimate=5;
  output;
  end;
Gender="W"; BoatClass="1x";
```

```
do i=1 to 10;
  estimate=5;
  output;
  end;
Gender="W"; BoatClass="2-";
do i=1 to 13;
  estimate=5;
  output;
  end;
keep BoatClass Gender estimate;
*/
/*
proc univariate plot data=dat4;
var DriveAccelMax;
class Participant;
by BoatClass Gender;
run;
*/
/*
proc sort data=dat4;
by BoatClass Gender Participant Side;

proc standard data=dat4 mean=0 out=dat5;
var &pred;
by BoatClass Gender Participant;
run;

title "100*log(&pred), simple stats with each participlant rescaled to zero";
proc means maxdec=0 data=dat5;
var &pred;
class BoatClass Gender;
run;
*/
*proc print data=dat5(obs=500);run;

proc standard data=dat6 out=dat7 mean=0;
var &predboat;
by BoatClass Gender BoatID;

proc standard data=dat7 out=dat8 std=0.5;
var &predboat;
by BoatClass Gender;
run;

proc standard data=dat8 out=dat9 mean=0;
var PowerPeach StrokeRate;
by BoatClass Gender;
run;

/*
```

```
*check dataset;

proc means;
var &predboat;
by BoatClass Gender;
run;

*proc print data=dat7(obs=400);run;
proc freq data=dat7;
tables strokeset*BoatID/norow nocol nopercent;
by BoatClass Gender;
run;
*/

data cov lsm lsmdiff lsmdiff1 lsmdiff2  lsmest est solf solr pred pred1;

%let convcrit=CONVH=1E-8 convf=1E-8;

ods select none;
*ods listing close;
proc mixed data=dat9 covtest cl alpha=&alpha &nob &convcrit;
class BoatID Race StrokeSet Date;
model &dep=PowerPeach StrokeRate &predboat/outp=pred s residual ddfm=sat
alphap=&alpha ddfm=sat; *better without ddfm=sat?;
*model &dep=PowerPeach &predboat/outp=pred s residual ddfm=sat alphap=&alpha
ddfm=sat; *better without ddfm=sat?;
*model &dep=PowerPeach/outp=pred s residual ddfm=sat alphap=&alpha; *better
without ddfm=sat?;
*model &dep=PowerPeach &predboat.MeanResc &predboat/outp=pred s residual
ddfm=sat alphap=&alpha ddfm=sat; *better without ddfm=sat?;
*model &dep=PowerCubRoot PowerCubRoot*PowerCubRoot/outp=pred s residual
ddfm=sat alphap=&alpha ddfm=sat; *better without ddfm=sat?;
estimate "Intercept" int 1/cl alpha=&alpha;
estimate "PowerPeach /%" PowerPeach 1/cl alpha=&alpha;
estimate "StrokeRate /%" StrokeRate 1/cl alpha=&alpha;
*estimate "PowerCubRoot /%" PowerCubRoot 1/cl alpha=&alpha;
*estimate "PowerCubRoot^2 /%^2" PowerCubRoot*PowerCubRoot 1/cl alpha=&alpha;
*estimate "&predboat.Mean 2SD" &predboat.MeanResc 1/cl alpha=&alpha;
estimate "&predboat 2SD" &predboat 1/cl alpha=&alpha;
*random int &predboat/subject=BoatID type=un s cl alpha=&alpha;
random int PowerPeach/subject=BoatID s cl alpha=&alpha &type;
*random PowerPeach/subject=BoatID s cl alpha=&alpha;
random &predboat/subject=BoatID s cl alpha=&alpha;
random StrokeSet/subject=BoatID s cl alpha=&alpha;
*random StrokeSet Date/s cl alpha=&alpha;
repeated/group=BoatID;
/*
lsmestimate Device*SerialNumber "NK-Vicon:" 0;
lsmestimate Device*SerialNumber
  "Unit 1100827" 1 0 0 0  0 0 0  0 0 0  -1 0 0 0,
```

```
  "Unit 1101134" 0 1 0 0  0 0 0  0 0 0  0 -1 0 0,
  "Unit 1101819" 0 0 1 0  0 0 0  0 0 0  0 0 -1 0,
  "Unit 1101823" 0 0 0 1  0 0 0  0 0 0  0 0 0 -1
  /cl alpha=0.1;
*/
&parms;
*parms 5 5  5 5 5 5 5 5 5 5 5 5 5;
*parms/pdata=pdata;
ods output classlevels=clev;
ods output covparms=cov;
ods output lsmeans=lsm;
ods output diffs=lsmdiff;
ods output estimates=est;
ods output solutionf=solf;
ods output solutionr=solr;
ods output lsmestimates=lsmest;
by BoatClass Gender;
*where Gender="W" and BoatClass="2-";
*where Gender="M" and BoatClass="1x";
run;
ods select all;

title1 "&dep predicted by PowerPeach StrokeRate &predboat in a log-log mixed
model";

title2 "Class levels; Race not currently in the model";
*title3 "StrokeSet=0 is for boat predicted means";
proc print data=clev noobs; run;

title2 "Random effects, to check on adequacy of the model";
proc print data=cov noobs;
by BoatClass Gender;
run;

*proc print data=clev;run;
*proc print data=cov;run;
*proc print data=est;run;
*by BoatClass Gender;
run;

*proc print data=cov;run;
/*
proc print data=clev;run;
proc print data=cov;run;
proc print data=est;run;


proc print data=lsm;run;
proc print data=solr;run;
proc print data=decodeset;run;
```

```
*by BoatClass Gender;
run;
*/

data pred1;
set pred;
/*
if &logflag then do;
  *&pred=exp(&pred/100);
  &dep=exp(&dep/100);
  pred=exp(pred/100);
  end;
*/

*proc print data=pred;run;

title2 "Raw residuals vs predicteds";
*title2 "Standardized residuals vs predicteds";
/*options ls=80 ps=36;
proc plot data=pred1;
plot StudentResid*pred;
by BoatClass Gender;
run;
*/
/*
proc sort data=pred1;
by BoatClass Gender StrokeSet;

ods graphics / reset width=12cm height=10cm imagemap attrpriority=none;
proc sgplot data=pred1; *uniform=all;
scatter x=pred y=Resid/markerattrs=(size=3 color=black symbol=circlefilled)
filledoutlinedmarkers MARKERFILLATTRS=(color=black);
*scatter x=StrokeNo y=Resid/markerattrs=(size=3 color=black symbol=circlefilled)
filledoutlinedmarkers MARKERFILLATTRS=(color=black);
refline 0/axis=y lineattrs=(pattern=dot thickness=1 color=blue);
by BoatClass Gender;
*where Gender="M" and BoatClass="2-" and StrokeSet=36;
run;
ods graphics / reset;
*/
/*
proc plot data=pred1;
plot (&dep &pred)*StrokeNo;
by BoatClass Gender StrokeSet Side;
where Gender="M" and BoatClass="2-" and StrokeSet=36;
run;

options ps=52 ls=100;
proc print data=pred1;
```

```
var BoatClass Gender BoatID Date Race StrokeSet StrokeNo AvBoatVel &dep  pred
resid Studentresid;
format &dep pred 5.&decdep studentresid 5.1;
by BoatClass Gender;
where Resid<-200;
*where Gender="M" and BoatClass="2-" and StrokeSet=36;
run;
*/
option ls=90;
options ls=100 ps=50;
data pred2;
set pred1;
if abs(StudentResid)>4.5;

options ps=52 ls=100;
proc print data=pred2;
var BoatClass Gender BoatID Date Race StrokeSet StrokeNo &dep pred resid
Studentresid;
title2 "Outliers (Standardized residual >4.5)";
format &dep 5.&decdep studentresid 5.1;
by BoatClass Gender;
run;
option ls=90;

/*
title2 "Predicted mean power of boats at overall mean and max boat speed, no wind";
data pred1;
set pred;
if PredictAt ne "";
CLpm=(Upper-Lower)/2;
rename pred=PredictedPower;

proc sort data=pred1;
by descending PredictAt BoatClass Gender;

proc print data=pred1;
var PredictAt Gender BoatID BoatClass StrokeSet PredictAt Race AvBoatVel
PredictedPower CLpm DF      Alpha Lower   Upper;
format AvBoatVel 5.1 PredictedPower CLpm DF     Lower  Upper 5.0;
by descending PredictAt BoatClass Gender;
run;
*/

*thresholds via given smallest important;
data thresholds;
*set stdsd;
Units="Raw";
if &logflag then Units="%";
magnithresh=&MagniThresh;
if &logflag=0 then do; *these raw thresholds are actually via standardization;
```

```
Threshold="small   "; DeltaMeanBene=magnithresh; DeltaMeanHarm=-magnithresh;
SDthreshold=abs(magnithresh)/2; output;
  Threshold="moderate"; DeltaMeanBene=magnithresh*3; DeltaMeanHarm=-
magnithresh*3; SDthreshold=abs(DeltaMeanBene)/2; output;
  Threshold="large"; DeltaMeanBene=magnithresh*6; DeltaMeanHarm=-
magnithresh*6; SDthreshold=abs(DeltaMeanBene)/2; output;
  Threshold="v.large"; DeltaMeanBene=magnithresh*10; DeltaMeanHarm=-
magnithresh*10; SDthreshold=abs(DeltaMeanBene)/2; output;
  Threshold="x.large"; DeltaMeanBene=magnithresh*20; DeltaMeanHarm=-
magnithresh*20; SDthreshold=abs(DeltaMeanBene)/2; output;
  end;
else do;
  magnithresh=100*log(1+magnithresh/100);
  Threshold="small   "; DeltaMeanBene=100*exp(magnithresh/100)-100;
DeltaMeanHarm=100*exp(-magnithresh/100)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2)-100; output;
  Threshold="moderate"; DeltaMeanBene=100*exp(magnithresh/100*3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*3)-100; output;
  Threshold="large"; DeltaMeanBene=100*exp(magnithresh/100*1.6/0.3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*1.6/0.3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*1.6/0.3)-100; output;
  Threshold="v.large"; DeltaMeanBene=100*exp(magnithresh/100*2.5/0.3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*2.5/0.3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*2.5/0.3)-100; output;
  Threshold="x.large"; DeltaMeanBene=100*exp(magnithresh/100*4.0/0.3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*4.0/0.3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*4.0/0.3)-100; output;
  end;

title2 "&dep magnitude thresholds (&unitsrawlog), based on a given smallest important
for means of &magnithresh (&unitsrawlog).";
title3 "Factors for the thresholds for moderate, large, v.large and x.large are .9/.3x,
1.6/.3x, 2.5/.3x and 4/.3x the smallest important,";
title4 "i.e., competitive athlete thresholds; thresholds for SDs are half those for means.";
proc print noobs;
var Threshold Units DeltaMeanBene DeltaMeanHarm SDthreshold;
format DeltaMeanBene DeltaMeanHarm SDthreshold 5.&decdep;format
DeltaMeanBene DeltaMeanHarm SDthreshold 5.&decdep;
where &logflag=0;
run;

proc print noobs;
var Threshold Units DeltaMeanBene DeltaMeanHarm SDthreshold;
format DeltaMeanBene DeltaMeanHarm 5.&deceff SDthreshold 5.2;
where &logflag=1;
run;

data est1;
set est;
```

```
if estimate=0 then estimate=.;
array a estimate lower upper;
if &logflag=1 then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(upper-lower)/2;
*if index(Label,"RFDAv") and index(Label,BoatClass)=0 then delete;

title2 "Fixed effects (&unitsrawlog)";
title3 "Ignore the intercept; the PowerPeach is the index in V=kP^x";
proc print data=est1 noobs;
var BoatClass Gender label Estimate CLpm Lower Upper DF alpha;
format estimate CLpm lower upper 5.2;
by BoatClass Gender;
run;

title2 "MBD for fixed effects with a given smallest important for means of
&magnithresh (&unitsrawlog)";
data est1;
set est;
if index(Label,"2SD");
length Prob $ 8 Magni $ 4;
MagniThresh=&MagniThresh;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh))/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh))/StdErr,DF);
if &LogFlag=1 then do;
  if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  else do;
    ChancePos=100*(1-ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  end;

ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
ClinFlag=1; *want inferences to be clinical;
*if index(label,"2SD") then ClinFlag=0; *covariates definitely need to be non-clinical;
*clinical inferences;
if clinflag then do;
Precision="unclear";
ChPos=ChancePos; ChNeg=ChanceNeg;
if MagniThresh<0 then do;
  ChPos=ChanceNeg; ChNeg=ChancePos;
  end;
if ChNeg<0.5 then do;
  Precision="@25/.5%";
```

```
  if ChNeg<0.1 then Precision="@5/.1% ";
  Magni="bene";
  if ChNeg<0.1 and ChPos>5 then Prob="unlikely";
  if ChPos>25 then Prob="possibly";
  if ChPos>75 then Prob="likely  ";
  if ChPos>95 then Prob="v.likely";
  if ChPos>99.5 then Prob="m.likely";
  if ChPos<25 and prob ne "unlikely" then do;
    Magni="triv";
    if ChanceTriv>25 then Prob="possibly";
    if ChanceTriv>75 then Prob="likely  ";
    if ChanceTriv>95 then Prob="v.likely";
    if ChanceTriv>99.5 then Prob="m.likely";
    end;
  end;
else do; *ChNeg>0.5;
  if ChPos<25 then do;
    Precision="@25/.5%";
    if ChPos<5 then Precision="@5/.1% ";
    if ChanceTriv>25 then do;
      Magni="triv";Prob="possibly";
      if ChanceTriv>75 then Prob="likely";
      if ChanceTriv>95 then Prob="v.likely";
      if ChanceTriv>99.5 then Prob="m.likely";
      end;
    if ChNeg>25 then do;
      Magni="harm";Prob="possibly";
      if ChNeg>75 then Prob="likely  ";
      if ChNeg>75 then Prob="likely  ";
      if ChNeg>95 then Prob="v.likely";
      if ChNeg>99.5 then Prob="m.likely";
      end;
    end;
  end;
if Precision="unclear" and
  (MagniThresh>0 and ORPosNeg>25/75/(0.5/99.5) or StdzedMagniThresh<0 and
ORNegPos>25/75/(0.5/99.5))
  then do;
  Precision="OR>66.3";
  Magni="bene";
  if ChPos>25 then Prob="possibly";
  if ChPos>75 then Prob="likely  ";
  if ChPos>95 then Prob="v.likely";
  if ChPos>99.5 then Prob="m.likely";
  end;
output;
end;
*mechanistic inferences;
ClinFlag=0;
Precision="unclear";
```

```
Prob="";
Magni="     ";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then Precision="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then Precision="@99%  ";
if Precision ne "unclear" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if Precision ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
*end;
output;

data est2;
set est1;
if estimate=0 or estimate=. then do;
  estimate=.; magnithresh=.; magni=""; Precision=""; Prob=""; Units=""; Magni="";
Precision=.;
  end;
array a estimate lower upper;
if &logflag then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(Upper-lower)/2;
rename df=DegFree;
if index(Label,".")=1 then Label=substr(Label,2);
run;

*options ls=135 ps=80;
title3 "Units for estimates, confidence limits and smallest important are &unitsrawlog";
title4 "Non-clinical inferences";
proc print data=est2 noobs;
where clinflag=0;
var BoatClass Gender label estimate CLpm lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos Prob Magni Precision;
format estimate CLpm lower upper MagniThresh 5.&deceff Probt best5. ChanceNeg
ChanceTriv
  ChancePos 5.1 DegFree 5.0;
*by BoatClass Gender;
run;
```

```
data covall;
*length Device $ 5 Group $ 12;
set cov;
if covparm ne "UN(2,1)";
alpha=&alpha;
DegFree=2*ZValue**2;
*if Lower=. then do;
  *Lower=DegFree*estimate/CINV(1-alpha/2,DegFree);
  *Upper=DegFree*estimate/CINV(alpha/2,DegFree);
  *conf limits via normal dist;
if StdErr ne 0 then do;
  lower=estimate+probit(alpha/2)*StdErr;
  upper=estimate-probit(alpha/2)*StdErr;
  end;
array a estimate lower upper;
do over a;
  a=sign(a)*sqrt(abs(a));
  end;
if &logflag=1 then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(upper-lower)/2;
*if substr(covparm,1,2) ne "UN" then CLpm=(upper-lower)/2;
CLtd=sqrt(upper/lower);
drop StdErr--ProbZ;
if covparm="UN(1,1)" then covparm="Intercept";
if covparm="UN(2,2)" then covparm="PowerPeach";
Group=substr(Group,8);

title2 "Random effects as standard deviations (&unitsrawlog)";
title3 "Intercept is boat indiv differences in mean efficiency";
title4 "PowerPeach is boat indiv differences in x, where V=kP^x";
title5 "&predboat is boat indiv differences in slope";
title6 "StrokeSet is boat mean differences between races, e.g., due to changes in
environment";
*title5 "Date is mean differences between dates, e.g., due to changes in environment";
title7 "Residual is the stroke to stroke variation in speed";
proc print noobs data=covall;
var BoatClass Gender covparm subject Group estimate CLpm lower upper alpha;
format estimate lower upper CLpm 5.&deceff CLtd 5.2 DegFree 5.0;
by BoatClass Gender;
run;
/*
proc print noobs data=covall;
var BoatClass Gender covparm subject Group estimate CLpm lower upper alpha;
format estimate lower upper CLpm 5.2 CLtd 5.2 DegFree 5.0;
*by BoatClass Gender;
where covparm="PowerPeach";
run;
```

```
*/

title2 "Non-clinical MBD for random effects";
title3 "Magnithresh is half the given smallest difference of &magnithresh
(&unitsrawlog) for means";
title4 "&predboat is boat indiv differences in slope";
*title6 "Non-clinical MBD for SD representing random effects";
*title3 "Intercept is boat indiv differences in mean efficiency";
*title4 "StrokeSet is boat mean differences between races, e.g., due to changes in
environment";
*title5 "Date is mean differences between dates, e.g., due to changes in environment";
*title6 "Residual is the stroke to stroke variation in speed";
data cov1;
set cov;
if covparm="UN(1,1)" then covparm="Intercept";
if covparm="UN(2,2)" then covparm="PowerPeach";
if covparm="&predboat";
*if substr(Group,8)="NK" or substr(Group,8)="Peach"; *add or modify, depending on
the analysis;
*lower=estimate+probit(alpha/2)*StdErr; *for those models where nobound did not
work;
*upper=estimate-probit(alpha/2)*StdErr;
DF=999;
MagniThresh=abs(&MagniThresh)/2;
if &logflag then Magnithresh=100*exp(log(1+abs(&magnithresh)/100)/2)-100;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh)**2)/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh)**2)/StdErr,DF);
if &logflag then do;
  *if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-
(100*log(1+MagniThresh/100))**2)/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+(100*log(1+MagniThresh/100))**2)/StdErr,DF);
    end;
ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
*ClinFlag=0; *want all inferences to be non-clinical for within-subject random effect;
*mechanistic inferences;
Precision="unclear";
Prob="        ";
Magni="     ";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then Precision="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then Precision="@99%  ";
if Precision ne "unclear" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
```

```
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if Precision ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
if not stderr then do; Magni="";Precision=""; end;
Group=substr(Group,8);

data cov2;
set cov1;
alpha=&alpha;
*if covparm ne "Residual" then do;
  lower=estimate+probit(alpha/2)*StdErr;
  upper=estimate-probit(alpha/2)*StdErr;
*  end;
array a estimate lower upper;
do over a;
  a=sign(a)*sqrt(abs(a));
  end;
DegFree=2*Zvalue**2;
array r SD lower upper;
if &logflag=1 then do over r;
  r=100*exp(r/100)-100;
  end;
CLpm=(upper-lower)/2;
*if substr(covparm,1,2) ne "UN" then CLpm=(upper-lower)/2;
CLtd=sqrt(upper/lower);
run;

title6 "Non-clinical MBD for SD representing random effects";
title7 "Magnithresh is half the given smallest difference for means";
proc print data=cov2 noobs;
var BoatClass Gender covparm Subject Group estimate CLpm lower upper alpha
  MagniThresh ChanceNeg ChanceTriv ChancePos Prob Magni Precision;
format estimate CLpm lower upper 5.&deceff MagniThresh 5.2 ChanceNeg ChanceTriv
  ChancePos 5.1 DF 5.0;
*by BoatClass Gender;
run;

*proc print data=solr;run;
*random-effect solution;
data solr1;
set solr;
/*
Alpha=&alpha;
t=tinv(1-&alpha/2,DF);
```

```
LowerCL=Estimate-t*StdErrPred;
UpperCL=Estimate+t*StdErrPred;
*/
CLpm=(Upper-Lower)/2;
drop StdErrPred tValue Probt;
format Estimate Lower Upper CLpm 5.&deceff DF 5.0;
if effect="Intercept" or effect="StrokeSet" or effect="&predboat";

proc sort;
by Effect BoatClass Gender Estimate;
/*
title2 "Random-effect solution (&unitsrawlog)";
title3 "Intercept is boat indiv differences in mean efficiency";
*title4 "Warning: after adjusting for between-boat differences in mean &predboat";
proc print data=solr1 noobs;
var Effect BoatClass Gender BoatID Estimate     DF     Alpha  Lower  Upper
     CLpm;
where effect="Intercept";
by Effect BoatClass Gender;
run;
*/
data predboat;
set solr1;
if effect="&predboat";
*drop StrokeSet;

title2 "Random-effect solution (&unitsrawlog)";
title3 "&predboat is relative difference from mean slope";
proc print data=predboat noobs;
var Effect BoatClass Gender BoatID Estimate     DF     Alpha  Lower  Upper
     CLpm;
by Effect BoatClass Gender;
run;

/*
data date;
set solr1;
if effect="Date";
drop BoatID StrokeSet;

title2 "Random-effect solution (&unitsrawlog)";
title3 "Date is mean differences between dates, e.g., due to changes in environment";
proc print data=date noobs;
var Effect BoatClass Gender Date    Estimate     DF     Alpha  Lower  Upper
     CLpm;
by Effect BoatClass Gender;
run;
*/
/*
data strokeset;
```

```
set solr1;
if effect="StrokeSet" and estimate ne 0; *with subjec=BoatID we get lots of zeros;
drop BoatID Date;

proc sort;
by BoatClass Gender StrokeSet;

proc sort data=decodeset;
by BoatClass Gender StrokeSet;

*proc print data=strokeset;run;

data strokeset1;
merge decodeset strokeset;
by BoatClass Gender StrokeSet;

title2 "Random-effect solution (&unitsrawlog)";
title3 "StrokeSet is boat mean differences between races within dates, e.g., due to
changes in environment";
proc print noobs;
var BoatClass Gender StrokeSet BoatID Race Date Time Estimate Lower Upper CLpm
Alpha;
format Estimate Lower Upper CLpm 5.&deceff;
by BoatClass Gender;
run;
*/

/*
data strokeside;
set solr1;
if effect="Participant*Side";
drop StrokeSet;

*proc print data=decodeside;run;

data strokeside1;
merge decodeside strokeside;
by BoatClass Gender Participant Side;

proc sort;
by BoatClass Gender BoatID Side;

title3 "Participant and StrokeSide are consistent efficiency across strokes and stroke
sets";
title4 "(additional to the fixed effect of Side)";
proc print noobs;
var BoatClass Gender BoatID Side Participant Estimate Lower Upper CLpm Alpha;
by BoatClass Gender;
format Estimate Lower Upper CLpm 5.&deceff;
by BoatClass Gender;
```

```
run;
*/

*proc print data=cov;run;

/*
data lsm1;
set lsm;
array a estimate lower upper;
do over a;
  *a=100*exp(a/100)-100; *for modeling of change scores;
  if &logflag=1 then a=exp(a/100);
  end;
CLpm=(upper-lower)/2;
drop Effect Stderr tValue Probt;

title2 "Least-squares means";
options ls=80 ps=82;
proc print data=lsm1 noobs;
*var BoatClass Gender estimate lower upper CLpm DF;
format estimate lower upper CLpm 5.&decdep;
by BoatClass Gender;
run;
options ps=52;

data lsmdiff1;
set lsmdiff;
array a estimate lower upper;
if &logflag=1 then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(upper-lower)/2;
drop stderr tValue probt;

options ps=80;
title2 "Least-squares mean differences (&unitsrawlog)";
proc print data=lsmdiff1 noobs;
var Race _Race Side _Side estimate CLpm lower upper alpha;
format estimate CLpm lower upper 5.&deceff DF 5.0; *Probt best5.;
*where &logflag=0;
by BoatClass Gender;
*where Effect="Device" or Effect="SerialNumber(Device)" and Device=_Device;
run;

*title2 "MBI for least-square mean diffs with a given smallest important for means of
&magnithresh (&unitsrawlog)";
title2 "MBI for the above with a given smallest important for means of &magnithresh
(&unitsrawlog)";
data lsmdiff1;
*set lsmdiff;
```

```
set lsmdiff;
*if index("&dep","Ratio") or "&dep"="TrainPerfPercent"; *measures where lsmeans
are differences from coach prescription;
length Prob $ 8 Magni $ 4;
MagniThresh=&MagniThresh;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh))/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh))/StdErr,DF);
if &LogFlag=1 then do;
  if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  else do;
    ChancePos=100*(1-ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  end;
ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
ClinFlag=1; *want all inferences to be clinical initially;
*if index(label,"2SD") then ClinFlag=0; *covariates definitely need to be non-clinical;

*clinical inferences;
if clinflag then do;
ChPos=ChancePos; ChNeg=ChanceNeg;
if MagniThresh<0 then do;
  ChPos=ChanceNeg; ChNeg=ChancePos;
  end;
Prob=""; Magni=""; Precision="unclear";
if ChNeg<0.5 then do;
  Precision="@25/.5%";
  if ChNeg<0.1 then Precision="@5/.1% ";
  if ChanceTriv>25 then Magni="triv";
  if ChPos>25 then Magni="bene";
  Prob="possibly";
  if ChPos>75 or ChanceTriv>75 then Prob="likely  ";
  if ChPos>95 or ChanceTriv>95 then Prob="v.likely";
  if ChPos>99.5 or ChanceTriv>99.5 then Prob="m.likely";
  end;
else do; *i.e., ChNeg>0.5;
  if ChPos<25 then do;
    Precision="@25/.5%";
    if ChPos<5 then Precision="@5/.1% ";
    if ChanceTriv>25 then Magni="triv";
    if ChNeg>25 then Magni="harm";
    Prob="possibly";
    if ChNeg>75 or ChanceTriv>75 then Prob="likely  ";
    if ChNeg>95 or ChanceTriv>95 then Prob="v.likely";
    if ChNeg>99.5 or ChanceTriv>99.5 then Prob="m.likely";
```

```
    end;
  end;
if Precision="unclear" and
  (MagniThresh>0 and ORPosNeg>25/75/(0.5/99.5) or MagniThresh<0 and
ORNegPos>25/75/(0.5/99.5))
  then do;
  Precision="OR>66.3";
  Magni="bene";
  if ChPos>25 then Prob="possibly";
  if ChPos>75 then Prob="likely  ";
  if ChPos>95 then Prob="v.likely";
  if ChPos>99.5 then Prob="m.likely";
  end;
output;
end;

*mechanistic inferences;
ClinFlag=0;
Precision="unclear";
Prob="";
Magni="";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then Precision="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then Precision="@99%  ";
if Precision ne "unclear" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if Precision ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
*end;
output;

data lsmdiff2;
Units="Raw";
if &logflag then Units="%";
set lsmdiff1;
if estimate=0 then do;
  estimate=.; magnithresh=.; magni=""; Precision=""; Prob=""; Units="";
  end;
array a estimate lower upper;
```

```
if &logflag then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(Upper-lower)/2;
rename df=DegFree;
run;

*options ls=135 ps=80;
title3 "Non-clinical inferences";
title4 "Magnithresh is the given smallest important difference for means";
title5 "Units for estimates, confidence limits and smallest important are &unitsrawlog";
proc print data=lsmdiff2 noobs;
where clinflag=0;
var Race Side _Race _Side Units estimate CLpm lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos Prob Magni Precision;
format  DeviceMean ViconMean estimate CLpm lower upper MagniThresh 5.&deceff
Probt best5. ChanceNeg ChanceTriv
  ChancePos 5.1 DegFree 5.0;
by BoatClass Gender;
*where clinflag=0 and (Effect="Device" or Effect="SerialNumber(Device)" and
Device=_Device);
run;
*/
/*
*lsmestimates;
data lsmest1;
set lsmest;
array a estimate lower upper;
if &logflag=1 then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(upper-lower)/2;
if estimate=0 then do; estimate=.; DF=.; end;
drop stderr tValue probt;

options ps=80;
title2 "Least-squares mean estimates (&unitsrawlog)";
proc print data=lsmest1 noobs;
var Position SRgroup Label Estimate--CLpm;
format estimate CLpm lower upper 5.&deceff DF 5.0 Probt best5.;
*where &logflag=0;
*by BoatClass Gender;
*where Effect="Device" or Effect="SerialNumber(Device)" and Device=_Device;
run;

title2 "MBI for least-square mean estimates with a given smallest important for means
of &magnithresh (&unitsrawlog)";
data lsmest1;
set lsmest;
```

```
*if index("&dep","Ratio") or "&dep"="TrainPerfPercent"; *measures where lsmeans
are differences from coach prescription;
length Prob $ 8 Magni $ 4;
MagniThresh=&MagniThresh;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh))/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh))/StdErr,DF);
if &LogFlag=1 then do;
  if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  else do;
    ChancePos=100*(1-ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  end;
ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
ClinFlag=1; *want all inferences to be clinical initially;
*if index(label,"2SD") then ClinFlag=0; *covariates definitely need to be non-clinical;

*clinical inferences;
if clinflag then do;
ChPos=ChancePos; ChNeg=ChanceNeg;
if MagniThresh<0 then do;
  ChPos=ChanceNeg; ChNeg=ChancePos;
  end;
Prob=""; Magni=""; Precision="unclear";
if ChNeg<0.5 then do;
  Precision="@25/.5%";
  if ChNeg<0.1 then Precision="@5/.1% ";
  if ChanceTriv>25 then Magni="triv";
  if ChPos>25 then Magni="bene";
  Prob="possibly";
  if ChPos>75 or ChanceTriv>75 then Prob="likely  ";
  if ChPos>95 or ChanceTriv>95 then Prob="v.likely";
  if ChPos>99.5 or ChanceTriv>99.5 then Prob="m.likely";
  end;
else do; *i.e., ChNeg>0.5;
  if ChPos<25 then do;
    Precision="@25/.5%";
    if ChPos<5 then Precision="@5/.1% ";
    if ChanceTriv>25 then Magni="triv";
    if ChNeg>25 then Magni="harm";
    Prob="possibly";
    if ChNeg>75 or ChanceTriv>75 then Prob="likely  ";
    if ChNeg>95 or ChanceTriv>95 then Prob="v.likely";
    if ChNeg>99.5 or ChanceTriv>99.5 then Prob="m.likely";
    end;
```

```
  end;
if Precision="unclear" and
  (MagniThresh>0 and ORPosNeg>25/75/(0.5/99.5) or MagniThresh<0 and
ORNegPos>25/75/(0.5/99.5))
  then do;
  Precision="OR>66.3";
  Magni="bene";
  if ChPos>25 then Prob="possibly";
  if ChPos>75 then Prob="likely  ";
  if ChPos>95 then Prob="v.likely";
  if ChPos>99.5 then Prob="m.likely";
  end;
output;
end;

*mechanistic inferences;
ClinFlag=0;
Precision="unclear";
Prob="";
Magni="";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then Precision="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then Precision="@99%  ";
if Precision ne "unclear" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if Precision ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
*end;
output;

data lsmest2;
Units="Raw";
if &logflag then Units="%";
set lsmest1;
if estimate=0 then do;
  estimate=.; magnithresh=.; magni=""; Precision=""; Prob=""; Units="";
  end;
array a estimate lower upper;
if &logflag then do over a;
```

```
  a=100*exp(a/100)-100;
  end;
CLpm=(Upper-lower)/2;
rename df=DegFree;
run;


*options ls=135 ps=80;
title3 "Non-clinical inferences";
title4 "Magnithresh is the given smallest important difference for means";
title5 "Units for estimates, confidence limits and smallest important are &unitsrawlog";
proc print data=lsmest2 noobs;
where clinflag=0;
var Position SRgroup Label Units estimate CLpm lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos Prob Magni Precision;
format estimate CLpm lower upper MagniThresh 5.&deceff Probt best5. ChanceNeg
ChanceTriv
  ChancePos 5.1 DegFree 5.0;
*by BoatClass Gender;
*where clinflag=0 and (Effect="Device" or Effect="SerialNumber(Device)" and
Device=_Device);
run;
*/
%mend;

%let alpha=0.1;
%let decdep=1;
%let deceff=1;
%let nob=;
%let convcrit=CONVH=1E-8 convf=1E-8;
%let StdzedMagniThresh=0.20; *smallest stdized beneficial change;
%let MagniThresh=0.3; *smallest beneficial change;
%let parms=;
*let title1=;
%let subset=if StrokeNo>10;

%let dep=AvBoatVel;
%let logflag=1;
%let nob=;
%let parms=;
%let type=type=un;
/*
%let predboat=StrokeRate; *StrokeRate is now another predictor;
%let logflagpred=0;
%let decpredboat=1;
*/
/*
*this one allows neg variance for M2-for StrokeRate;
%let subset=if StrokeNo>10 and Gender="M" and BoatClass="2-";
%let predboat=StrokeRate;
```

```
%let nob=nobound;
%let type=;
%let parms=parms 1 0 0 0 3 3 3;
%anaboat;
%let nob=;
%let subset=if StrokeNo>10;
%let parms=;
%let type=type=un;
*/

%let predboat=BoatVelRange;
%let logflagpred=0;
%let decpredboat=2;
%anaboat;

%let predboat=RecovAccelPeak;
%let decpredboat=2;
%anaboat;

%let predboat=DriveAccelMax;
%let decpredboat=2;
%anaboat;

%let predboat=DriveAccelMin;
%let decpredboat=2;
%anaboat;

%let predboat=Distperstroke;
%let decpredboat=2;
%anaboat;

%let predboat=VCatchLost;
%let decpredboat=2;
%anaboat;

%let predboat=TcatchToVmin;
%let decpredboat=2;
%anaboat;

%let predboat=RecovDecelTime;
%let decpredboat=2;
%anaboat;
%let nob=;

/*
*this one allows neg variance for W1x for RecovDecelTime;
%let subset=if StrokeNo>10 and Gender="W" and BoatClass="1x";
%let predboat=RecovDecelTime;
%let decpredboat=2;
%let nob=nobound;
```

```
%let type=;
%let parms=parms 1 0 0 0 3 3 3 3 3 3 3 3;
%anaboat;
%let nob=;
%let subset=if StrokeNo>10;
%let parms=;
%let type=type=un;
*/
```

Appendix W: Study Four statistical analysis SAS script for oar predictors (one predictor measure per oar)

```
libname ss '/folders/myshortcuts/ExternalFiles/Projects/_VU Melbourne/Ana
Holt/Study 3';
*libname ss '/folders/myshortcuts/PhD/Study 3_Technical Determinants/Raw data';
*StrokeRate is now a predictor, along with PowerPeach;

*VBCaM2-     VBCaVMHM2-         M        2-        Heat;

data dat1;
set ss.study3;
attrib _character_ _numeric_ label="";
rename DriveAccelPointAngle=DriAccPointAng
RecovDecelPointAngle=RecDecPointAng
  RatioDriveToTotaPC=RatDriveToTotaPC;
RatioMaxMeanF=MaxGateForce/MeanGateForce;
run;
*proc print data=ss.study3(obs=100);
run;

%macro anaoar;
data _null_;
if &logflag then call symput('unitsrawlog',"percent");
else call symput('unitsrawlog',"raw");
run;

/*
proc sort data=dat1;
by Gender Participant Race;

ods graphics / reset width=20cm height=16cm imagemap attrpriority=none;
title "Scatterplot of &dep vs StrokeNo";
proc sgplot data=dat1 uniform=scale;
styleattrs
  datacolors=(black blue red pink greenyellow)
  datalinepatterns=(dot)
  datacontrastcolors=(black blue red pink greenyellow)
  datasymbols=(circlefilled);
  *datasymbols=(circlefilled squarefilled diamondfilled trianglefilled);
*reg x=Vicon y=&dep/nomarkers name='def' group=DeviceUnit;
*reg x=Vicon1 y=Identity/nomarkers name='def' lineattrs=(color=black pattern=dash
thickness=0.5);
scatter x=StrokeNo y=&dep/markerattrs=(size=5) filledoutlinedmarkers name='abc'
group=Race;
*scatter x=StrokeNo y=&dep/groupdisplay=cluster clusterwidth=0.3
markerattrs=(size=8) filledoutlinedmarkers group=DeviceUnit  name='abc';
*series x=&dep y=MeanLine /lineattrs=(pattern=dash thickness=1 color=black);
*keylegend 'def' /noborder titleattrs=(size=16) valueattrs=(size=16);
keylegend 'abc' /title="Race:" noborder titleattrs=(size=16) valueattrs=(size=16);
```

```
yaxis label="&dep" labelpos=top labelattrs=(size=16) valueattrs=(size=16);
xaxis label="StrokeNo" labelattrs=(size=16) valueattrs=(size=16);
refline 10/axis=x lineattrs=(pattern=dot thickness=1 color=black);
*refline MeanDep/axis=x lineattrs=(pattern=dash thickness=0.25 color=black);
by Gender Participant;
*where Participant="VMTW2-";
where StrokeNo>3; * and  Participant="VMTW2-";
run;
ods graphics/reset;
*/
proc sort data=dat1;
by Date Time BoatID ;

data dat2;
retain StrokeSet 0;
set dat1;
if lag(Date) ne Date or lag(Time) ne Time or lag(BoatID) ne BoatID then
StrokeSet=StrokeSet+1;
&subset;
/*
if &logflag=1 then &dep=100*log(&dep);
if &logflagpred=1 then &pred=100*log(&pred);
*/
if BoatID="VBCaVMHM2-" and Race="Heat" then delete;
run;

proc sort data=dat2;
by BoatClass Gender BoatID StrokeSet StrokeNo;
run;

data bow;
set dat2;
if Side="B";
keep Time &predoar StrokeRate BoatClass Gender Race BoatID Date Participant
StrokeSet StrokeNo StrokeDuration PowerPeach AvBoatVel;
rename Time=TimeB &predoar=&predoar.Bow Participant=RowerBow
PowerPeach=PowerPeachBow;

*proc print data=bow(obs=50);run;

data stroke;
set dat2;
if Side="S";
keep Time &predoar BoatClass Gender Race BoatID Participant StrokeSet StrokeNo
PowerPeach WindDirectionDec WindAve;
rename Time=TimeS &predoar=&predoar.Stroke Participant=RowerStroke
PowerPeach=PowerPeachStroke;

data dat4;
merge bow(in=a) stroke(in=b);
```

```
by BoatClass Gender BoatID StrokeSet StrokeNo;
if a and not b or b and not a then delete; *only 10 obs, plus VRMLM1x for one race;
PowerPeach=PowerPeachBow+PowerPeachStroke;
Time=TimeB;
if TimeB="" then Time=TimeS;
drop TimeB TimeS;
if Race="Trials" then Race="Final";
if Race="Rep" or Race="Semi" then Race="Heat";
*if BoatID="AHHLM1x" or  BoatID="ANKLM1x" or  BoatID="SOMLM1x" or
BoatID="VACM1x" or  BoatID="VENM1x";
*if Gender="W" and BoatClass="2-";

data decodeset;
set dat4;
if lag(StrokeSet) ne StrokeSet;
keep BoatClass Gender StrokeSet Date Time Race BoatID;
run;

*proc print data=bow(obs=100);run;
/*
proc sort data=dat1;
by BoatClass Gender Participant Side;

data decodeside;
set dat1;
if lag(BoatID) ne BoatID or lag(Side) ne Side;
keep BoatClass Gender BoatID Side Participant;

*proc print noobs;
run;
*/

title "Within-boat simple stats for AvBoatVel (m/s)";
title2 "Nobs is the number of stroke sets";
proc means noprint data=dat4;
var AvBoatVel;
by BoatClass Gender BoatID StrokeSet;
*where Side="B";
output out=meansd mean=WthnBoatMean std=WthnBoatSD;

proc means maxdec=2;
var WthnBoatMean WthnBoatSD;
class BoatClass Gender;
run;

title "Within-boat simple stats for PowerPeach (W)";
title2 "Nobs is the number of stroke sets";
proc means noprint data=dat4;
var PowerPeach;
by BoatClass Gender BoatID StrokeSet;
```

```
*where Side="B";
output out=meansd mean=WthnBoatMean std=WthnBoatSD;

proc means maxdec=0;
var WthnBoatMean WthnBoatSD;
class BoatClass Gender;
run;

title "Within-boat simple stats for StrokeRate (spm)";
title2 "Nobs is the number of stroke sets";
proc means noprint data=dat4;
var StrokeRate;
by BoatClass Gender BoatID StrokeSet;
*where Side="B";
output out=meansd mean=WthnBoatMean std=WthnBoatSD;

data dat5;
set dat4;
PowerCubRoot=PowerPeach**(1/3);
if &logflag then do;
  &dep=100*log(&dep);
  PowerPeach=100*log(PowerPeach);
  PowerCubRoot=100*log(PowerCubRoot);
  StrokeRate=100*log(StrokeRate);
  end;
run;

*proc print data=dat3(obs=1000);
run;

title "Within-boat simple stats for log-transformed AvBoatVel";
title2 "Nobs is the number of stroke sets";
proc means noprint data=dat5;
var AvBoatVel;
by BoatClass Gender BoatID StrokeSet;
*where Side="B";
output out=meansd mean=WthnBoatMean std=WthnBoatSD;

proc means maxdec=1;
var WthnBoatMean WthnBoatSD;
class BoatClass Gender;
run;

title "Within-boat simple stats for log-transformed PowerPeach";
title2 "Nobs is the number of stroke sets";
proc means noprint data=dat5;
var PowerPeach;
by BoatClass Gender BoatID StrokeSet;
*where Side="B";
output out=meansd mean=WthnBoatMean std=WthnBoatSD;
```

```
proc means maxdec=1;
var WthnBoatMean WthnBoatSD;
class BoatClass Gender;
run;

title "Between- and within-boat simple stats for &predoar";
title2 "Nobs is the number of boats";
proc means noprint data=dat5;
var &predoar.Bow &predoar.Stroke &dep PowerPeach;
by BoatClass Gender BoatID;
*where Side="B";
output out=predoarmean mean=&predoar.BowMean &predoar.StrokeMean &dep.Mean
PowerPeachMean std=WthnBowSD WthnStrokeSD;

data predoarmean1;
set predoarmean;
&predoar.BowMeanResc=&predoar.BowMean;
&predoar.StrokeMeanResc=&predoar.StrokeMean;

proc standard data=predoarmean1 out=predoarmean2 mean=0 std=0.5;
var &predoar.BowMeanResc &predoar.StrokeMeanResc;
by BoatClass Gender;

proc means maxdec=&decpredoar;
var &predoar.BowMean &predoar.StrokeMean WthnBowSD WthnStrokeSD;
class BoatClass Gender;
run;
/*
proc means maxdec=1;
var &predoar.BowMeanResc &predoar.StrokeMeanResc;
class BoatClass Gender;
run;
*/

title "Between-boat simple stats for log-transformed &dep.Mean and
PowerPeachMean";
title2 "Compare the SDs: we expect SD for PowerPeach to be more than 3x the SD for
AvBoatVel";
title3 "N is the number of boats";
proc means maxdec=1 data=predoarmean n mean std min max;
var &dep.Mean PowerPeachMean;
class BoatClass Gender;
run;

data dat6;
merge dat5 predoarmean2(keep=BoatClass Gender BoatID &predoar.BowMean
&predoar.StrokeMean &predoar.BowMeanResc &predoar.StrokeMeanResc);
by BoatClass Gender BoatID;
run;
```

```
/*
title "Within-boat correlations";
ods select none;
proc corr data=dat5 nosimple outp=corrs;
var AvBoatVel PowerPeach &predboat;
by BoatClass Gender BoatID StrokeSet;
*ods output FisherPearsonCorr=fish;
run;
ods select all;

*proc print data=corrs(obs=20);run;

data corrs1;
retain SortOrder;
set corrs;
if _Type_="CORR";
drop _type_ ;
if _name_ ne "";
if _name_="AvBoatVel" then SortOrder=0;
if lag(_name_) ne _name_ then SortOrder=SortOrder+1;
rename _name_=Predictor;
array a AvBoatVel PowerPeach &predboat;
do over a;
  if a=1 then a=.;
  end;

proc sort;
by BoatClass Gender SortOrder Predictor;

proc means noprint;
var AvBoatVel PowerPeach &predboat;
by BoatClass Gender SortOrder Predictor;
output out=corrs2 mean=;
run;

proc print noobs;
var BoatClass Gender Predictor AvBoatVel PowerPeach &predboat;
by BoatClass Gender;
format _numeric_ 5.2;
run;
*/
/*
proc freq data=dat4;
tables Participant*Race/nocol norow nopercent nocum;
by BoatClass Gender;
run
*/
/*
proc print data=dat3; *(obs=10);
```

```
where BoatID ne "VRMLM1x";
run;
*/
/*
data pdata;
Gender="M"; BoatClass="1x";
estimate=6;output;estimate=2;output; output;
estimate=9;output;estimate=5;output;estimate=10;output;estimate=6;output;
do i=1 to 6;
  estimate=5;
  output;
  end;
Gender="M"; BoatClass="2-";
do i=1 to 7;
  estimate=5;
  output;
  end;
Gender="W"; BoatClass="1x";
do i=1 to 10;
  estimate=5;
  output;
  end;
Gender="W"; BoatClass="2-";
do i=1 to 13;
  estimate=5;
  output;
  end;
keep BoatClass Gender estimate;
*/
/*
proc univariate plot data=dat4;
var DriveAccelMax;
class Participant;
by BoatClass Gender;
run;
*/
/*
proc sort data=dat4;
by BoatClass Gender Participant Side;

proc standard data=dat4 mean=0 out=dat5;
var &pred;
by BoatClass Gender Participant;
run;

title "100*log(&pred), simple stats with each participlant rescaled to zero";
proc means maxdec=0 data=dat5;
var &pred;
class BoatClass Gender;
run;
```

```
*/
*proc print data=dat5(obs=500);run;

proc standard data=dat6 out=dat7 mean=0;
var &predoar.Bow &predoar.Stroke;
by BoatClass Gender BoatID;

proc standard data=dat7 out=dat8 std=0.5;
var &predoar.Bow &predoar.Stroke;
by BoatClass Gender;
run;

proc standard data=dat8 out=dat9 mean=0;
var PowerPeach StrokeRate;
by BoatClass Gender;
run;
/*
*check dataset;

proc means;
var &predboat;
by BoatClass Gender;
run;

*proc print data=dat7(obs=400);run;
proc freq data=dat7;
tables strokeset*BoatID/norow nocol nopercent;
by BoatClass Gender;
run;
*/

data cov lsm lsmdiff lsmdiff1 lsmdiff2  lsmest est solf solr pred pred1;

%let convcrit=CONVH=1E-8 convf=1E-8;

ods select none;
*ods listing close;
proc mixed data=dat9 covtest cl alpha=&alpha &nob &convcrit;
class BoatID Race StrokeSet Date;
*model &dep=PowerPeach/outp=pred s residual ddfm=sat alphap=&alpha; *better
without ddfm=sat?;
model &dep=PowerPeach StrokeRate &predoar.Bow &predoar.Stroke/outp=pred s
residual ddfm=sat alphap=&alpha ddfm=sat; *better without ddfm=sat?;
*model &dep=PowerPeach &predboat.MeanResc &predboat/outp=pred s residual
ddfm=sat alphap=&alpha ddfm=sat; *better without ddfm=sat?;
*model &dep=PowerCubRoot PowerCubRoot*PowerCubRoot/outp=pred s residual
ddfm=sat alphap=&alpha ddfm=sat; *better without ddfm=sat?;
estimate "Intercept" int 1/cl alpha=&alpha;
estimate "PowerPeach /%" PowerPeach 1/cl alpha=&alpha;
estimate "StrokeRate /%" StrokeRate 1/cl alpha=&alpha;
```

```
*estimate "PowerCubRoot /%" PowerCubRoot 1/cl alpha=&alpha;
*estimate "PowerCubRoot^2 /%^2" PowerCubRoot*PowerCubRoot 1/cl alpha=&alpha;
*estimate "&predboat.Mean 2SD" &predboat.MeanResc 1/cl alpha=&alpha;
estimate "&predoar.Bow  2SD" &predoar.Bow 1/cl alpha=&alpha;
estimate "&predoar.Stroke 2SD" &predoar.Stroke 1/cl alpha=&alpha;
estimate "Sum bow+stroke 2SD"  &predoar.Bow 1 &predoar.Stroke 1/cl alpha=&alpha;
estimate "Mean bow+stroke 2SD"  &predoar.Bow .5 &predoar.Stroke .5/cl
alpha=&alpha;
random int PowerPeach/subject=BoatID s cl alpha=&alpha type=vc;
*random &predoar.Bow &predoar.Stroke/subject=BoatID s cl alpha=&alpha type=un;
*gave too many zeros;
random &predoar.Bow &predoar.Stroke/subject=BoatID s cl alpha=&alpha;
random StrokeSet/subject=BoatID s cl alpha=&alpha;
*random int/subject=BoatID s cl alpha=&alpha;
*random StrokeSet/subject=BoatID s cl alpha=&alpha;
*random StrokeSet Date/s cl alpha=&alpha;
*random &predboat/subject=BoatID s cl alpha=&alpha;
repeated/group=BoatID;
/*
lsmestimate Device*SerialNumber "NK-Vicon:" 0;
lsmestimate Device*SerialNumber
  "Unit 1100827" 1 0 0 0  0 0 0  0 0 0  -1 0 0 0,
  "Unit 1101134" 0 1 0 0  0 0 0  0 0 0  0 -1 0 0,
  "Unit 1101819" 0 0 1 0  0 0 0  0 0 0  0 0 -1 0,
  "Unit 1101823" 0 0 0 1  0 0 0  0 0 0  0 0 0 -1
  /cl alpha=0.1;
*/
&parms;
*parms 5 5  5 5 5 5 5 5 5 5 5 5 5;
*parms/pdata=pdata;
ods output classlevels=clev;
ods output covparms=cov;
ods output lsmeans=lsm;
ods output diffs=lsmdiff;
ods output estimates=est;
ods output solutionf=solf;
ods output solutionr=solr;
ods output lsmestimates=lsmest;
by BoatClass Gender;
*where Gender="W" and BoatClass="2-";
*where Gender="M" and BoatClass="1x";
run;
ods select all;

title1 "&dep predicted by PowerPeach StrokeRate &predoar in a log-log mixed model";

title2 "Class levels; Race not currently in the model";
*title3 "StrokeSet=0 is for boat predicted means";
proc print data=clev noobs; run;
```

```
title2 "Random effects, to check on adequacy of the model";
proc print data=cov noobs;
by BoatClass Gender;
run;

*proc print data=clev;run;
*proc print data=cov;run;
*proc print data=est;run;
*by BoatClass Gender;
run;

*proc print data=cov;run;
/*
proc print data=clev;run;
proc print data=cov;run;
proc print data=est;run;


proc print data=lsm;run;
proc print data=solr;run;
proc print data=decodeset;run;
*by BoatClass Gender;
run;
*/

data pred1;
set pred;
/*
if &logflag then do;
  *&pred=exp(&pred/100);
  &dep=exp(&dep/100);
  pred=exp(pred/100);
  end;
*/

*proc print data=pred;run;

title2 "Raw residuals vs predicteds";
*title2 "Standardized residuals vs predicteds";
/*options ls=80 ps=36;
proc plot data=pred1;
plot StudentResid*pred;
by BoatClass Gender;
run;
*/
/*
proc sort data=pred1;
by BoatClass Gender StrokeSet;

ods graphics / reset width=12cm height=10cm imagemap attrpriority=none;
```

```
proc sgplot data=pred1; *uniform=all;
scatter x=pred y=Resid/markerattrs=(size=3 color=black symbol=circlefilled)
filledoutlinedmarkers MARKERFILLATTRS=(color=black);
*scatter x=StrokeNo y=Resid/markerattrs=(size=3 color=black symbol=circlefilled)
filledoutlinedmarkers MARKERFILLATTRS=(color=black);
refline 0/axis=y lineattrs=(pattern=dot thickness=1 color=blue);
by BoatClass Gender;
*where Gender="M" and BoatClass="2-" and StrokeSet=36;
run;
ods graphics / reset;
*/
/*
proc plot data=pred1;
plot (&dep &pred)*StrokeNo;
by BoatClass Gender StrokeSet Side;
where Gender="M" and BoatClass="2-" and StrokeSet=36;
run;

options ps=52 ls=100;
proc print data=pred1;
var BoatClass Gender BoatID Date Race StrokeSet StrokeNo AvBoatVel &dep  pred
resid Studentresid;
format &dep pred 5.&decdep studentresid 5.1;
by BoatClass Gender;
where Resid<-200;
*where Gender="M" and BoatClass="2-" and StrokeSet=36;
run;
*/
option ls=90;
options ls=100 ps=50;
data pred2;
set pred1;
if abs(StudentResid)>4.5;

options ps=52 ls=100;
proc print data=pred2;
var BoatClass Gender BoatID Date Race StrokeSet StrokeNo &dep pred resid
Studentresid;
title2 "Outliers (Standardized residual >4.5)";
format &dep 5.&decdep studentresid 5.1;
by BoatClass Gender;
run;
option ls=90;

/*
title2 "Predicted mean power of boats at overall mean and max boat speed, no wind";
data pred1;
set pred;
if PredictAt ne "";
CLpm=(Upper-Lower)/2;
```

```
rename pred=PredictedPower;

proc sort data=pred1;
by descending PredictAt BoatClass Gender;

proc print data=pred1;
var PredictAt Gender BoatID BoatClass StrokeSet PredictAt Race AvBoatVel
PredictedPower CLpm DF     Alpha Lower   Upper;
format AvBoatVel 5.1 PredictedPower CLpm DF    Lower  Upper 5.0;
by descending PredictAt BoatClass Gender;
run;
*/

*thresholds via given smallest important;
data thresholds;
*set stdsd;
Units="Raw";
if &logflag then Units="%";
magnithresh=&MagniThresh;
if &logflag=0 then do; *these raw thresholds are actually via standardization;
Threshold="small   "; DeltaMeanBene=magnithresh; DeltaMeanHarm=-magnithresh;
SDthreshold=abs(magnithresh)/2; output;
  Threshold="moderate"; DeltaMeanBene=magnithresh*3; DeltaMeanHarm=-
magnithresh*3; SDthreshold=abs(DeltaMeanBene)/2; output;
  Threshold="large"; DeltaMeanBene=magnithresh*6; DeltaMeanHarm=-
magnithresh*6; SDthreshold=abs(DeltaMeanBene)/2; output;
  Threshold="v.large"; DeltaMeanBene=magnithresh*10; DeltaMeanHarm=-
magnithresh*10; SDthreshold=abs(DeltaMeanBene)/2; output;
  Threshold="x.large"; DeltaMeanBene=magnithresh*20; DeltaMeanHarm=-
magnithresh*20; SDthreshold=abs(DeltaMeanBene)/2; output;
  end;
else do;
  magnithresh=100*log(1+magnithresh/100);
  Threshold="small   "; DeltaMeanBene=100*exp(magnithresh/100)-100;
DeltaMeanHarm=100*exp(-magnithresh/100)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2)-100; output;
  Threshold="moderate"; DeltaMeanBene=100*exp(magnithresh/100*3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*3)-100; output;
  Threshold="large"; DeltaMeanBene=100*exp(magnithresh/100*1.6/0.3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*1.6/0.3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*1.6/0.3)-100; output;
  Threshold="v.large"; DeltaMeanBene=100*exp(magnithresh/100*2.5/0.3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*2.5/0.3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*2.5/0.3)-100; output;
  Threshold="x.large"; DeltaMeanBene=100*exp(magnithresh/100*4.0/0.3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*4.0/0.3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*4.0/0.3)-100; output;
  end;
```

```
title2 "&dep magnitude thresholds (&unitsrawlog), based on a given smallest important
for means of &magnithresh (&unitsrawlog).";
title3 "Factors for the thresholds for moderate, large, v.large and x.large are .9/.3x,
1.6/.3x, 2.5/.3x and 4/.3x the smallest important,";
title4 "i.e., competitive athlete thresholds; thresholds for SDs are half those for means.";
proc print noobs;
var Threshold Units DeltaMeanBene DeltaMeanHarm SDthreshold;
format DeltaMeanBene DeltaMeanHarm SDthreshold 5.&decdep;format
DeltaMeanBene DeltaMeanHarm SDthreshold 5.&decdep;
where &logflag=0;
run;

proc print noobs;
var Threshold Units DeltaMeanBene DeltaMeanHarm SDthreshold;
format DeltaMeanBene DeltaMeanHarm 5.&deceff SDthreshold 5.2;
where &logflag=1;
run;

data est1;
set est;
if estimate=0 then estimate=.;
array a estimate lower upper;
if &logflag=1 then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(upper-lower)/2;
*if index(Label,"RFDAv") and index(Label,BoatClass)=0 then delete;

title2 "Fixed effects (&unitsrawlog)";
title3 "Ignore the intercept; the PowerPeach is the index in V=kP^x";
proc print data=est1 noobs;
var BoatClass Gender label Estimate CLpm Lower Upper DF alpha;
format estimate CLpm lower upper 5.2;
by BoatClass Gender;
run;

title2 "MBD for fixed effects with a given smallest important for means of
&magnithresh (&unitsrawlog)";
data est1;
set est;
if index(Label,"2SD");
length Prob $ 8 Magni $ 4;
MagniThresh=&MagniThresh;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh))/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh))/StdErr,DF);
if &LogFlag=1 then do;
  if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF);
    end;
```

```
  else do;
    ChancePos=100*(1-ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  end;

ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
ClinFlag=1; *want inferences to be clinical;
*if index(label,"2SD") then ClinFlag=0; *covariates definitely need to be non-clinical;
*clinical inferences;
if clinflag then do;
ClearOrNot="unclear";
ChPos=ChancePos; ChNeg=ChanceNeg;
if MagniThresh<0 then do;
  ChPos=ChanceNeg; ChNeg=ChancePos;
  end;
if ChNeg<0.5 then do;
  ClearOrNot="@25/.5%";
  if ChNeg<0.1 then ClearOrNot="@5/.1% ";
  Magni="bene";
  if ChNeg<0.1 and ChPos>5 then Prob="unlikely";
  if ChPos>25 then Prob="possibly";
  if ChPos>75 then Prob="likely  ";
  if ChPos>95 then Prob="v.likely";
  if ChPos>99.5 then Prob="m.likely";
  if ChPos<25 and prob ne "unlikely" then do;
    Magni="triv";
    if ChanceTriv>25 then Prob="possibly";
    if ChanceTriv>75 then Prob="likely  ";
    if ChanceTriv>95 then Prob="v.likely";
    if ChanceTriv>99.5 then Prob="m.likely";
    end;
  end;
else do; *ChNeg>0.5;
  if ChPos<25 then do;
    ClearOrNot="@25/.5%";
    if ChPos<5 then ClearOrNot="@5/.1% ";
    if ChanceTriv>25 then do;
      Magni="triv";Prob="possibly";
      if ChanceTriv>75 then Prob="likely";
      if ChanceTriv>95 then Prob="v.likely";
      if ChanceTriv>99.5 then Prob="m.likely";
      end;
    if ChNeg>25 then do;
      Magni="harm";Prob="possibly";
      if ChNeg>75 then Prob="likely  ";
      if ChNeg>75 then Prob="likely  ";
      if ChNeg>95 then Prob="v.likely";
```

```
      if ChNeg>99.5 then Prob="m.likely";
      end;
    end;
  end;
if ClearOrNot="unclear" and
  (MagniThresh>0 and ORPosNeg>25/75/(0.5/99.5) or StdzedMagniThresh<0 and
ORNegPos>25/75/(0.5/99.5))
  then do;
  ClearOrNot="OR>66.3";
  Magni="bene";
  if ChPos>25 then Prob="possibly";
  if ChPos>75 then Prob="likely  ";
  if ChPos>95 then Prob="v.likely";
  if ChPos>99.5 then Prob="m.likely";
  end;
output;
end;
*mechanistic inferences;
ClinFlag=0;
ClearOrNot="unclear";
Prob="";
Magni="     ";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then ClearOrNot="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then ClearOrNot="@99%  ";
if ClearOrNot ne "unclear" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if ClearOrNot ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
*end;
output;

data est2;
set est1;
if estimate=0 or estimate=. then do;
  estimate=.; magnithresh=.; magni=""; clearornot=""; Prob=""; Units=""; Magni="";
ClearOrNot=.;
  end;
array a estimate lower upper;
```

```
if &logflag then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(Upper-lower)/2;
rename df=DegFree;
if index(Label,".")=1 then Label=substr(Label,2);
run;

*options ls=135 ps=80;
title3 "Units for estimates, confidence limits and smallest important are &unitsrawlog";
title4 "Non-clinical inferences";
proc print data=est2 noobs;
where clinflag=0;
var BoatClass Gender label estimate CLpm lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos Prob Magni ClearOrNot;
format estimate CLpm lower upper MagniThresh 5.&deceff Probt best5. ChanceNeg
ChanceTriv
  ChancePos 5.1 DegFree 5.0;
by BoatClass Gender;
run;

data covall0;
set cov;
lagest=lag(estimate); lagse=lag(stderr);
output;
if index(covparm,"Stro")>1 or covparm="StrokeArcAngleStroke" then do; *end of the
value is chopped off for longest variable names;
  covparm="Sum bow+stroke";
  estimate=estimate+lagest; *assume these are independent, so variances and SEs add as
shown;
  StdErr=sqrt(Stderr**2+lagse**2);
  Zvalue=Estimate/StdErr;
  output;
  covparm="Mean bow+stroke";
  estimate=estimate/2; *assume these are independent, so variances and SEs add as
shown;
  StdErr=StdErr/2;
  Zvalue=Estimate/StdErr;
  output;
  end;
drop lagest lagse;

data covall;
*length Device $ 5 Group $ 12;
set covall0;
if covparm ne "UN(2,1)";
*if covparm="UN(1,1)" then covparm="&predoar.bow";
*if covparm="UN(2,2)" then covparm="&predoar.stroke";
alpha=&alpha;
DegFree=2*ZValue**2;
```

```
*if Lower=. then do;
  *Lower=DegFree*estimate/CINV(1-alpha/2,DegFree);
  *Upper=DegFree*estimate/CINV(alpha/2,DegFree);
  *conf limits via normal dist;
if StdErr ne 0 then do;
  lower=estimate+probit(alpha/2)*StdErr;
  upper=estimate-probit(alpha/2)*StdErr;
  end;
array a estimate lower upper;
do over a;
  a=sign(a)*sqrt(abs(a));
  end;
if &logflag=1 then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(upper-lower)/2;
*if substr(covparm,1,2) ne "UN" then CLpm=(upper-lower)/2;
CLtd=sqrt(upper/lower);
drop StdErr--ProbZ;
Group=substr(Group,8);

title2 "Random effects as standard deviations (&unitsrawlog)";
title3 "Intercept is boat indiv differences in mean efficiency";
title4 "PowerPeach is boat indiv differences in index x in V=kP^x";
title5 "&predoar bow and stroke are boat indiv differences in slope";
title6 "Sum and Mean bow+stroke are sum and mean of the bow and stroke indiv diffs";
title7 "StrokeSet is boat mean differences between races, e.g., due to changes in
environment";
title8 "Residual is the stroke to stroke variation in speed";
proc print noobs data=covall;
var BoatClass Gender covparm subject Group estimate CLpm lower upper alpha;
format estimate lower upper CLpm 5.&deceff CLtd 5.2 DegFree 5.0;
by BoatClass Gender;
run;
/*
title3 "PowerPeach is boat indiv differences in index x in Speed=kPower^x";
title4 "with an extra decimal place";
proc print noobs data=covall;
var BoatClass Gender covparm subject Group estimate CLpm lower upper alpha;
format estimate lower upper CLpm 5.2 CLtd 5.2 DegFree 5.0;
*by BoatClass Gender;
where covparm="PowerPeach";
run;
*/

title2 "Non-clinical MBD for SD representing random effects";
*title3 "Intercept is boat indiv differences in mean efficiency";
title3 "Magnithresh is half the given smallest difference of &magnithresh
(&unitsrawlog) for means";
title4 "&predoar bow and stroke are boat indiv differences in slope";
```

```
title5 "Sum bow+stroke is a sum the bow and stroke indiv diffs";
*title6 "StrokeSet is boat mean differences between races, e.g., due to changes in
environment";
*title5 "Date is mean differences between dates, e.g., due to changes in environment";
*title5 "Residual is the stroke to stroke variation in speed";
data cov1;
set covall0;
if covparm="PowerPeach" or covparm="Intercept" or covparm="StrokeSet" then
delete;
*if covparm="UN(1,1)" then covparm="&predoar.bow";
*if covparm="UN(2,2)" then covparm="&predoar.stroke";
if covparm="UN(2,1)" or covparm="Residual" then delete;
*if substr(Group,8)="NK" or substr(Group,8)="Peach"; *add or modify, depending on
the analysis;
*lower=estimate+probit(alpha/2)*StdErr; *for those models where nobound did not
work;
*upper=estimate-probit(alpha/2)*StdErr;
DF=999;
MagniThresh=abs(&MagniThresh)/2;
if &logflag then Magnithresh=100*exp(log(1+abs(&magnithresh)/100)/2)-100;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh)**2)/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh)**2)/StdErr,DF);
if &logflag then do;
  *if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-
(100*log(1+MagniThresh/100))**2)/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+(100*log(1+MagniThresh/100))**2)/StdErr,DF);
    end;
ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
*ClinFlag=0; *want all inferences to be non-clinical for within-subject random effect;
*mechanistic inferences;
ClearOrNot="unclear";
Prob="        ";
Magni="     ";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then ClearOrNot="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then ClearOrNot="@99%  ";
if ClearOrNot ne "unclear" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if ClearOrNot ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
```

```
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
if not stderr then do; Magni="";ClearOrNot=""; end;
Group=substr(Group,8);

data cov2;
set cov1;
alpha=&alpha;
*if covparm ne "Residual" then do;
  lower=estimate+probit(alpha/2)*StdErr;
  upper=estimate-probit(alpha/2)*StdErr;
*  end;
array a estimate lower upper;
do over a;
  a=sign(a)*sqrt(abs(a));
  end;
DegFree=2*Zvalue**2;
array r SD lower upper;
if &logflag=1 then do over r;
  r=100*exp(r/100)-100;
  end;
CLpm=(upper-lower)/2;
*if substr(covparm,1,2) ne "UN" then CLpm=(upper-lower)/2;
CLtd=sqrt(upper/lower);
run;

proc print data=cov2 noobs;
var BoatClass Gender covparm Subject Group estimate CLpm lower upper alpha
  MagniThresh ChanceNeg ChanceTriv ChancePos Prob Magni ClearOrNot;
format estimate CLpm lower upper 5.&deceff MagniThresh 5.2 ChanceNeg ChanceTriv
  ChancePos 5.1 DF 5.0;
by BoatClass Gender;
run;

*proc print data=solr;run;
*random-effect solution;
data solr1;
set solr;
/*
Alpha=&alpha;
t=tinv(1-&alpha/2,DF);
LowerCL=Estimate-t*StdErrPred;
UpperCL=Estimate+t*StdErrPred;
*/
CLpm=(Upper-Lower)/2;
drop StdErrPred tValue Probt;
format Estimate Lower Upper CLpm 5.&deceff DF 5.0;
```

```
if effect="Intercept" or effect="StrokeSet" or effect="&predoar.Bow" or
effect="&predoar.Stroke";

proc sort;
by Effect BoatClass Gender Estimate;
/*
title2 "Random-effect solution (&unitsrawlog)";
title3 "Intercept is boat indiv differences in mean efficiency";
*title4 "Warning: after adjusting for between-boat differences in mean &predboat";
proc print data=solr1 noobs;
var Effect BoatClass Gender BoatID Estimate     DF     Alpha  Lower  Upper
        CLpm;
where effect="Intercept";
by Effect BoatClass Gender;
run;
*/
data predoar;
set solr1;
if effect="&predoar.Stroke" or effect="&predoar.Bow";
*drop StrokeSet;

title2 "Random-effect solution (&unitsrawlog)";
title3 "&predoar is relative difference from mean slope";
proc print data=predoar noobs;
var Effect BoatClass Gender BoatID Estimate     DF     Alpha  Lower  Upper
        CLpm;
by Effect BoatClass Gender;
run;

/*
data date;
set solr1;
if effect="Date";
drop BoatID StrokeSet;

title2 "Random-effect solution (&unitsrawlog)";
title3 "Date is mean differences between dates, e.g., due to changes in environment";
proc print data=date noobs;
var Effect BoatClass Gender Date    Estimate     DF     Alpha  Lower  Upper
        CLpm;
by Effect BoatClass Gender;
run;
*/
/*
data strokeset;
set solr1;
if effect="StrokeSet" and estimate ne 0; *with subjec=BoatID we get lots of zeros;
drop BoatID Date;

proc sort;
```

```
by BoatClass Gender StrokeSet;

proc sort data=decodeset;
by BoatClass Gender StrokeSet;

*proc print data=strokeset;run;

data strokeset1;
merge decodeset strokeset;
by BoatClass Gender StrokeSet;

title2 "Random-effect solution (&unitsrawlog)";
title3 "StrokeSet is boat mean differences between races within dates, e.g., due to
changes in environment";
proc print noobs;
var BoatClass Gender StrokeSet BoatID Race Date Time Estimate Lower Upper CLpm
Alpha;
format Estimate Lower Upper CLpm 5.&deceff;
by BoatClass Gender;
run;
*/

/*
data strokeside;
set solr1;
if effect="Participant*Side";
drop StrokeSet;

*proc print data=decodeside;run;

data strokeside1;
merge decodeside strokeside;
by BoatClass Gender Participant Side;

proc sort;
by BoatClass Gender BoatID Side;

title3 "Participant and StrokeSide are consistent efficiency across strokes and stroke
sets";
title4 "(additional to the fixed effect of Side)";
proc print noobs;
var BoatClass Gender BoatID Side Participant Estimate Lower Upper CLpm Alpha;
by BoatClass Gender;
format Estimate Lower Upper CLpm 5.&deceff;
by BoatClass Gender;
run;
*/

*proc print data=cov;run;
```

```
/*
data lsm1;
set lsm;
array a estimate lower upper;
do over a;
  *a=100*exp(a/100)-100; *for modeling of change scores;
  if &logflag=1 then a=exp(a/100);
  end;
CLpm=(upper-lower)/2;
drop Effect Stderr tValue Probt;

title2 "Least-squares means";
options ls=80 ps=82;
proc print data=lsm1 noobs;
*var BoatClass Gender estimate lower upper CLpm DF;
format estimate lower upper CLpm 5.&decdep;
by BoatClass Gender;
run;
options ps=52;

data lsmdiff1;
set lsmdiff;
array a estimate lower upper;
if &logflag=1 then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(upper-lower)/2;
drop stderr tValue probt;

options ps=80;
title2 "Least-squares mean differences (&unitsrawlog)";
proc print data=lsmdiff1 noobs;
var Race _Race Side _Side estimate CLpm lower upper alpha;
format estimate CLpm lower upper 5.&deceff DF 5.0; *Probt best5.;
*where &logflag=0;
by BoatClass Gender;
*where Effect="Device" or Effect="SerialNumber(Device)" and Device=_Device;
run;

*title2 "MBI for least-square mean diffs with a given smallest important for means of
&magnithresh (&unitsrawlog)";
title2 "MBI for the above with a given smallest important for means of &magnithresh
(&unitsrawlog)";
data lsmdiff1;
*set lsmdiff;
set lsmdiff;
*if index("&dep","Ratio") or "&dep"="TrainPerfPercent"; *measures where lsmeans
are differences from coach prescription;
length Prob $ 8 Magni $ 4;
MagniThresh=&MagniThresh;
```

```
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh))/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh))/StdErr,DF);
if &LogFlag=1 then do;
  if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  else do;
    ChancePos=100*(1-ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  end;
ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
ClinFlag=1; *want all inferences to be clinical initially;
*if index(label,"2SD") then ClinFlag=0; *covariates definitely need to be non-clinical;

*clinical inferences;
if clinflag then do;
ChPos=ChancePos; ChNeg=ChanceNeg;
if MagniThresh<0 then do;
  ChPos=ChanceNeg; ChNeg=ChancePos;
  end;
Prob=""; Magni=""; ClearOrNot="unclear";
if ChNeg<0.5 then do;
  ClearOrNot="@25/.5%";
  if ChNeg<0.1 then ClearOrNot="@5/.1% ";
  if ChanceTriv>25 then Magni="triv";
  if ChPos>25 then Magni="bene";
  Prob="possibly";
  if ChPos>75 or ChanceTriv>75 then Prob="likely  ";
  if ChPos>95 or ChanceTriv>95 then Prob="v.likely";
  if ChPos>99.5 or ChanceTriv>99.5 then Prob="m.likely";
  end;
else do; *i.e., ChNeg>0.5;
  if ChPos<25 then do;
    ClearOrNot="@25/.5%";
    if ChPos<5 then ClearOrNot="@5/.1% ";
    if ChanceTriv>25 then Magni="triv";
    if ChNeg>25 then Magni="harm";
    Prob="possibly";
    if ChNeg>75 or ChanceTriv>75 then Prob="likely  ";
    if ChNeg>95 or ChanceTriv>95 then Prob="v.likely";
    if ChNeg>99.5 or ChanceTriv>99.5 then Prob="m.likely";
    end;
  end;
if ClearOrNot="unclear" and
  (MagniThresh>0 and ORPosNeg>25/75/(0.5/99.5) or MagniThresh<0 and
ORNegPos>25/75/(0.5/99.5))
```

```
  then do;
  ClearOrNot="OR>66.3";
  Magni="bene";
  if ChPos>25 then Prob="possibly";
  if ChPos>75 then Prob="likely  ";
  if ChPos>95 then Prob="v.likely";
  if ChPos>99.5 then Prob="m.likely";
  end;
output;
end;

*mechanistic inferences;
ClinFlag=0;
ClearOrNot="unclear";
Prob="";
Magni="";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then ClearOrNot="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then ClearOrNot="@99%  ";
if ClearOrNot ne "unclear" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if ClearOrNot ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
*end;
output;

data lsmdiff2;
Units="Raw";
if &logflag then Units="%";
set lsmdiff1;
if estimate=0 then do;
  estimate=.; magnithresh=.; magni=""; clearornot=""; Prob=""; Units="";
  end;
array a estimate lower upper;
if &logflag then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(Upper-lower)/2;
rename df=DegFree;
```

```
run;

*options ls=135 ps=80;
title3 "Non-clinical inferences";
title4 "Magnithresh is the given smallest important difference for means";
title5 "Units for estimates, confidence limits and smallest important are &unitsrawlog";
proc print data=lsmdiff2 noobs;
where clinflag=0;
var Race Side _Race _Side Units estimate CLpm lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos Prob Magni ClearOrNot;
format  DeviceMean ViconMean estimate CLpm lower upper MagniThresh 5.&deceff
Probt best5. ChanceNeg ChanceTriv
  ChancePos 5.1 DegFree 5.0;
by BoatClass Gender;
*where clinflag=0 and (Effect="Device" or Effect="SerialNumber(Device)" and
Device=_Device);
run;
*/
/*
*lsmestimates;
data lsmest1;
set lsmest;
array a estimate lower upper;
if &logflag=1 then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(upper-lower)/2;
if estimate=0 then do; estimate=.; DF=.; end;
drop stderr tValue probt;

options ps=80;
title2 "Least-squares mean estimates (&unitsrawlog)";
proc print data=lsmest1 noobs;
var Position SRgroup Label Estimate--CLpm;
format estimate CLpm lower upper 5.&deceff DF 5.0 Probt best5.;
*where &logflag=0;
*by BoatClass Gender;
*where Effect="Device" or Effect="SerialNumber(Device)" and Device=_Device;
run;

title2 "MBI for least-square mean estimates with a given smallest important for means
of &magnithresh (&unitsrawlog)";
data lsmest1;
set lsmest;
*if index("&dep","Ratio") or "&dep"="TrainPerfPercent"; *measures where lsmeans
are differences from coach prescription;
length Prob $ 8 Magni $ 4;
MagniThresh=&MagniThresh;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh))/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh))/StdErr,DF);
```

```
if &LogFlag=1 then do;
  if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  else do;
    ChancePos=100*(1-ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  end;
ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
ClinFlag=1; *want all inferences to be clinical initially;
*if index(label,"2SD") then ClinFlag=0; *covariates definitely need to be non-clinical;

*clinical inferences;
if clinflag then do;
ChPos=ChancePos; ChNeg=ChanceNeg;
if MagniThresh<0 then do;
  ChPos=ChanceNeg; ChNeg=ChancePos;
  end;
Prob=""; Magni=""; ClearOrNot="unclear";
if ChNeg<0.5 then do;
  ClearOrNot="@25/.5%";
  if ChNeg<0.1 then ClearOrNot="@5/.1% ";
  if ChanceTriv>25 then Magni="triv";
  if ChPos>25 then Magni="bene";
  Prob="possibly";
  if ChPos>75 or ChanceTriv>75 then Prob="likely  ";
  if ChPos>95 or ChanceTriv>95 then Prob="v.likely";
  if ChPos>99.5 or ChanceTriv>99.5 then Prob="m.likely";
  end;
else do; *i.e., ChNeg>0.5;
  if ChPos<25 then do;
    ClearOrNot="@25/.5%";
    if ChPos<5 then ClearOrNot="@5/.1% ";
    if ChanceTriv>25 then Magni="triv";
    if ChNeg>25 then Magni="harm";
    Prob="possibly";
    if ChNeg>75 or ChanceTriv>75 then Prob="likely  ";
    if ChNeg>95 or ChanceTriv>95 then Prob="v.likely";
    if ChNeg>99.5 or ChanceTriv>99.5 then Prob="m.likely";
    end;
  end;
if ClearOrNot="unclear" and
  (MagniThresh>0 and ORPosNeg>25/75/(0.5/99.5) or MagniThresh<0 and
ORNegPos>25/75/(0.5/99.5))
  then do;
  ClearOrNot="OR>66.3";
```

```
  Magni="bene";
  if ChPos>25 then Prob="possibly";
  if ChPos>75 then Prob="likely  ";
  if ChPos>95 then Prob="v.likely";
  if ChPos>99.5 then Prob="m.likely";
  end;
output;
end;

*mechanistic inferences;
ClinFlag=0;
ClearOrNot="unclear";
Prob="";
Magni="";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then ClearOrNot="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then ClearOrNot="@99%  ";
if ClearOrNot ne "unclear" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if ClearOrNot ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
*end;
output;

data lsmest2;
Units="Raw";
if &logflag then Units="%";
set lsmest1;
if estimate=0 then do;
  estimate=.; magnithresh=.; magni=""; clearornot=""; Prob=""; Units="";
  end;
array a estimate lower upper;
if &logflag then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(Upper-lower)/2;
rename df=DegFree;
run;
```

```
*options ls=135 ps=80;
title3 "Non-clinical inferences";
title4 "Magnithresh is the given smallest important difference for means";
title5 "Units for estimates, confidence limits and smallest important are &unitsrawlog";
proc print data=lsmest2 noobs;
where clinflag=0;
var Position SRgroup Label Units estimate CLpm lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos Prob Magni ClearOrNot;
format estimate CLpm lower upper MagniThresh 5.&deceff Probt best5. ChanceNeg
ChanceTriv
  ChancePos 5.1 DegFree 5.0;
*by BoatClass Gender;
*where clinflag=0 and (Effect="Device" or Effect="SerialNumber(Device)" and
Device=_Device);
run;
*/
%mend;

%let dep=AvBoatVel;
%let logflag=1;
%let decdep=1;
%let deceff=1;

%let alpha=0.1;
%let nob=;
%let convcrit=CONVH=1E-8 convf=1E-8;
%let StdzedMagniThresh=0.20; *smallest stdized beneficial change;
%let MagniThresh=0.3; *smallest beneficial change;
%let parms=;
%let type=type=un; *not used;
%let subset=if StrokeNo>10;
*%let title1;

%let nob=;
%let parms=;
%let predoar=MeanGateForce;
%let decpredoar=0;
%let logflagpred=0;
%anaoar;

%let predoar=MaxGateForce;
%let decpredoar=0;
%let logflagpred=0;
%anaoar;

%let predoar=TimeToMaxForce;
%let decpredoar=2;
%let logflagpred=0;
%anaoar;
```

```
%let predoar=RatioMaxMeanF;
%let decpredoar=2;
%let logflagpred=0;
%anaoar;

%let predoar=RFDav;
%let decpredoar=0;
%let logflagpred=0;
%anaoar;

*angles;
%let predoar=FinishAngle;
%let decpredoar=1;
%let logflagpred=0;
%anaoar;

%let predoar=CatchAngle;
%let decpredoar=1;
%let logflagpred=0;
%anaoar;

%let predoar=StrokeArcAngle;
%let decpredoar=1;
%let logflagpred=0;
%anaoar;

%let predoar=MaxFAnglePeach;
%let decpredoar=1;
%let logflagpred=0;
%anaoar;

%let predoar=FinishSlipPeach;
%let decpredoar=1;
%let logflagpred=0;
%anaoar;

%let predoar=CatchSlipPeach;
%let decpredoar=1;
%let logflagpred=0;
%anaoar;

%let predoar=DriAccPointAng;
%let decpredoar=1;
%let logflagpred=0;
%anaoar;

%let predoar=RecDecPointAng;
%let decpredoar=1;
%let logflagpred=0;
%anaoar;
```

```
/*
%let predoar=MeanGateForce;
%let nob=nobound;
%let subset=if StrokeNo>10 and BoatClass="2-" and Gender="M";
%let parms=parms .4 0 .1 0 .1 3 2 2;
%let decpredoar=0;
%let logflagpred=0;
%anaoar;

%let predoar=MaxGateForce;
%anaoar;

%let predoar=StrokeArcAngle;
%let decpredoar=1;
%anaoar;

%let predoar=FinishSlipPeach;
%anaoar;

%let predoar=MaxGateForce;
%let decpredoar=0;
%let parms=parms 4 0 0 .6 4 2 4 2 4 5 2 3 3;
%let subset=if StrokeNo>10 and BoatClass="1x" and Gender="W";
%anaoar;

%let nob=;
%let subset=if StrokeNo>10;
%let parms=;
*/
```

Appendix X: Study Five data processing R script

```
# Load libraries required
library(seewave)
library(tidyverse)
library(readxl)

# Set the working directory
setwd("C:/Users/ana.holt/OneDrive/PhD/Study 6_Acceleration curve anaysis/Data
processing/Logan exported files")

# Import data from the spreadsheet and remove the metadata from the file
crew <- read_excel(".xlsx", sheet = "Sheet1") %>% # Change the filename/sheet as
appropriate
  select(1:7) %>%
  setNames(as.character(.[3,])) %>%
  slice(4:n())

# Run the butterworth filter
crew_accel <- crew %>%
  select(Time, `Acc(1)`, `V(Acc)`) %>%
  mutate(Time = as.numeric(Time),
         `Acc(1)` = as.numeric(`Acc(1)`),
         Filtered = bwfilter(wave = `Acc(1)`, f = 100, n = 4, to = 6,
                             bandpass = T, output = "matrix"))

# Find the start of each stroke and all the peaks
filter <- crew_accel %>%
  mutate(Stroke = if_else(Filtered < -0.5 & lag(Filtered >= -0.5), 1, 0),
         Stroke = cumsum(Stroke),
         Stroke = if_else(Stroke > 0, Stroke, NULL)) %>%
  fill(Stroke) %>%
  group_by(Stroke) %>%
  mutate(Start = if_else(Filtered == min(Filtered), Stroke, NULL)) %>%
  ungroup() %>%
  fill(Start) %>%
  select(-Stroke) %>%
  rename(Stroke = Start) %>%
  mutate(Stroke = Stroke + 1,
         Stroke = if_else(is.na(Stroke), 1, Stroke),
         Start = if_else(Stroke != lag(Stroke), 1, 0),
         Start = if_else(is.na(Start), 1, Start)) %>%
  group_by(Stroke) %>%
  mutate(Peaks = if_else(Filtered > lag(Filtered) & Filtered >= lead(Filtered) & Filtered
> 0, 1, 0)) %>%
  mutate(Dips = if_else(Filtered < lag(Filtered) & Filtered <= lead(Filtered),1,0))

# Find the max peak between 1/4 and 2/3 of each stroke
# Usually this is the max peak for the stroke but sometimes the first peak is higher and
occasionally the third is
```

```
max_peak <- filter %>%
  filter(Start == 1 | Peaks == 1) %>%
  group_by(Stroke) %>%
  mutate(Time_diff = Time - lag(Time),
         Time_diff = if_else(is.na(Time_diff), 0, Time_diff),
         Cum_time = cumsum(Time_diff),
         Phase = case_when(Cum_time < max(Cum_time) * 0.25 ~ 1,
                           Cum_time > max(Cum_time) * 0.66 ~ 3,
                           TRUE ~ 2)) %>%
  filter(Phase == 2) %>%
  mutate(Peak = if_else(Filtered == max(Filtered), 1, 0)) %>%
  filter(Peak == 1)

# Join the max peak dataframe back together with the main dataframe
filter1 <- left_join(filter, max_peak, by = c("Time", "V(Acc)", "Acc(1)", "Filtered",
"Stroke", "Start", "Peaks", "Dips")) %>%
  mutate(Peak = if_else(is.na(Peak), 0, Peak)) %>%
  select(-Time_diff, -Cum_time, -Phase)

# Find the 3rd major peak
peak3 <- filter1 %>%
  filter(Peaks == 1) %>%
  mutate(Phase = if_else(Time <= Time[which.max(Peak)] + 0.3, 1, 2)) %>%
  group_by(Stroke, Phase) %>%
  mutate(Third_peak = if_else(Phase == 2 & Filtered == max(Filtered), 1, 0)) %>%
  filter(Third_peak == 1)

# Join the 3rd major peak data back with the main dataframe
filter2 <- left_join(filter1, peak3, by = c("Time", "V(Acc)", "Acc(1)", "Filtered",
"Stroke", "Start", "Peak", "Peaks", "Dips")) %>%
  group_by(Stroke) %>%
  mutate(Third_peak = if_else(is.na(Third_peak), 0, Third_peak),
         Phase = case_when(Time <= Time[which.max(Peak)] ~ 1,
                           Time <= Time[which.max(Third_peak)] & Time >
Time[which.max(Peak)] ~ 2,
                           TRUE ~ 3))

# Find the 2nd dip
dip2 <- filter2 %>%
  group_by(Stroke, Phase) %>%
  filter(Phase == 2 & Dips == 1 & Filtered < 0.25) %>%
  slice(1) %>%
  mutate(Second_dip = 1)
  #filter(Phase == 2) %>%
  #mutate(Second_dip = if_else(Filtered == min(Filtered), 1, 0)) %>%
  #filter(Second_dip == 1)
#& Time >= Time[which.max(Peak)] + 0.3

# Join the 2nd dip data back with the main dataframe
```

```
filter3 <- left_join(filter2, dip2, by = c("Time", "V(Acc)", "Acc(1)", "Filtered",
"Stroke", "Start",
                                        "Peak", "Peaks", "Dips", "Phase", "Third_peak")) %>%
  group_by(Stroke) %>%
  mutate(Second_dip = if_else(is.na(Second_dip), 0, Second_dip),
         Phase = case_when(Time <= Time[which.max(Peak)] ~ 1,
                           Time <= Time[which.max(Second_dip)] & Time >
Time[which.max(Peak)] ~ 2,
                           Time <= Time[which.max(Third_peak)] & Time >
Time[which.max(Second_dip)] ~ 3,
                           TRUE ~ 4))

RateOfChange <- 0.02

# Find the 1st peak in the dataframe (not necessarily the 1st major peak)
first_peak <- filter3 %>%
  group_by(Stroke, Phase) %>%
  filter(Phase == 1 & Time != Time[which.max(Peak)] & Filtered > -0.1) %>%
  mutate(First_peak = if_else(Filtered - lag(Filtered) < RateOfChange,1,0)) %>%
  filter(First_peak == 1) %>%
  slice(1)


# Join the 1st major peak back with the main dataframe
filter4 <- left_join(filter3, first_peak, by = c("Time", "V(Acc)", "Acc(1)", "Filtered",
"Stroke", "Start",
                                              "Peak", "Peaks", "Dips", "Phase", "Third_peak",
"Second_dip")) %>%
  group_by(Stroke) %>%
  mutate(First_peak = if_else(is.na(First_peak), 0, First_peak),
         Phase = case_when(Time <= Time[which.max(First_peak)] ~ 1,
                           Time <= Time[which.max(Peak)] & Time >
Time[which.max(First_peak)] ~ 2,
                           Time <= Time[which.max(Second_dip)] & Time >
Time[which.max(Peak)] ~ 3,
                           Time <= Time[which.max(Third_peak)] & Time >
Time[which.max(Second_dip)] ~ 4,
                           TRUE ~ 5))

# Find the 1st dip
dip1 <- filter4 %>%
  group_by(Stroke, Phase) %>%
  filter(Phase == 2) %>%
  mutate(First_dip = if_else(lead(Filtered) > Filtered, 1,
                            if_else(lead(Filtered) >= Filtered & lag(Filtered) >= Filtered, 1, 0)))
%>%
        filter(First_dip == 1) %>%
        slice(1)
  #mutate(First_dip = if_else(Filtered == min(Filtered), 1, 0)) %>%
  #filter(First_dip == 1)
```

```
# Join the 1st dip data back with the main dataframe
filter5 <- left_join(filter4, dip1, by = c("Time", "V(Acc)", "Acc(1)", "Filtered",
"Stroke", "Start",
                                           "Peak", "Peaks", "Phase", "Third_peak", "Second_dip",
"First_peak", "Dips")) %>%
  group_by(Stroke) %>%
  mutate(First_dip = if_else(is.na(First_dip), 0, First_dip),
         Phase = case_when(Time <= Time[which.max(First_dip)] ~ 1,
                       Time <= Time[which.max(Peak)] & Time >
Time[which.max(First_dip)] ~ 2,
                       Time <= Time[which.max(Second_dip)] & Time >
Time[which.max(Peak)] ~ 3,
                       Time <= Time[which.max(Third_peak)] & Time >
Time[which.max(Second_dip)] ~ 4,
                       TRUE ~ 5)) %>%
  select(-First_peak)

# Find the 1st major peak
peak1 <- filter5 %>%
  group_by(Stroke, Phase) %>%
  filter(Phase == 1) %>%
  mutate(First_peak = if_else(Filtered == max(Filtered), 1, 0)) %>%
  filter(First_peak == 1)

# Join the 1st major peak data back with the main dataframe
# Phases are:
# 1. Start of stroke to 1st major peak
# 2. 1st major peak to 1st dip
# 3. 1st dip to 2nd major peak
# 4. 2nd major peak to 2nd dip
# 5. 2nd dip to 3rd major peak
# 6. 3rd major peak to beginning of next stroke
filter6 <- left_join(filter5, peak1, by = c("Time", "V(Acc)", "Acc(1)", "Filtered",
"Stroke", "Start",
                                      "Peak", "Peaks", "Phase", "Third_peak", "Second_dip",
"First_dip", "Dips")) %>%
  group_by(Stroke) %>%
  mutate(First_peak = if_else(is.na(First_peak), 0, First_peak),
         Phase = case_when(Time <= Time[which.max(First_peak)] ~ 1,
                       Time <= Time[which.max(First_dip)] & Time >
Time[which.max(First_peak)] ~ 2,
                       Time <= Time[which.max(Peak)] & Time >
Time[which.max(First_dip)] ~ 3,
                       Time <= Time[which.max(Second_dip)] & Time >
Time[which.max(Peak)] ~ 4,
                       Time <= Time[which.max(Third_peak)] & Time >
Time[which.max(Second_dip)] ~ 5,
                       TRUE ~ 6))
```

```
# Plots and summary calculations are below

# Plot of the stroke trace with the major peaks and dips marked
ggplot(filter6, aes(Time, Filtered, group = 1)) +
  #geom_path(aes(Time, `Acc(1)`, group = 0.8), col = "grey50") +
  geom_path(size = 1.1) +
  geom_point(data = filter(filter6, Start == 1), size = 3, col = "red") +
  geom_point(data = filter(filter6, Peak == 1), size = 3, col = "green3") +
  geom_point(data = filter(filter6, Third_peak == 1), size = 3, col = "blue") +
  geom_point(data = filter(filter6, Second_dip == 1), size = 3, col = "orange") +
  geom_point(data = filter(filter6, First_dip == 1), size = 4, col = "deeppink") +
  geom_point(data = filter(filter6, First_peak == 1), size = 3, col = "purple") +
  xlim(35, 55) + # Change these to view other parts of the piece
  ylim(-1.7, 1.0) +
  theme_classic() +
    theme(axis.text = element_text(size = 20, colour = "black"),
          axis.ticks.length = unit(0.25, "cm"),
          axis.line = element_line(colour = "black", size = 1),
          axis.ticks = element_line(colour = "black", size = 1),
          axis.title = element_text(size = 20, colour = "black"),
          axis.title.y = element_text(margin = margin(r = 0.5, unit = "cm")),
          axis.title.x = element_text(margin = margin(t = 0.5, unit = "cm"))) +
  labs(y = "Acceleration (g)", x = "Time (s)")

# Calculation of Phase time, mean jerk for each stroke
#calc_by_stroke <- filter6 %>%
#  group_by(Stroke, Phase) %>%
#  mutate(Acc_diff = Filtered - lag(Filtered),
#         Time_diff = Time - lag(Time),
#         Time_diff = if_else(is.na(Time_diff), 0, Time_diff)) %>%
#  summarise(PhaseLength = sum(Time_diff) + 0.01,
#            Jerk = sum(Acc_diff, na.rm = T) / PhaseLength,
#            Velocity = mean(as.numeric(`V(Acc)`), na.rm = T)) %>%
#  ungroup() %>%
#  mutate(Phase23 = if_else(Phase == 3, PhaseLength + lag(PhaseLength), NULL),
#         Phase34 = if_else(Phase == 4, PhaseLength + lag(PhaseLength), NULL),
#         Phase61 = if_else(Phase == 1, PhaseLength + lag(PhaseLength), NULL),
#         Phase56 = if_else(Phase == 6, PhaseLength + lag(PhaseLength), NULL))

# Calculation of Phase time, mean jerk for each stroke
calc_by_stroke <- filter6 %>%
  #group_by(Stroke) %>%
  #mutate(PhaseLengthPerc = n() / 100) %>%
  group_by(Stroke, Phase) %>%
  mutate(Acc_diff = Filtered - lag(Filtered),
         Time_diff = Time - lag(Time),
         Time_diff = if_else(is.na(Time_diff), 0, Time_diff)) %>%
  summarise(PhaseLength = sum(Time_diff) + 0.01,
            Jerk = sum(Acc_diff, na.rm = T) / PhaseLength,
            Velocity = mean(as.numeric(`V(Acc)`), na.rm = T)) %>%
```

```
      #PhaseLengthPerc = round((PhaseLength / mean(PhaseLengthPerc) * 100),
digits = 2)) %>%
  ungroup() %>%
  mutate(Phase23 = if_else(Phase == 3 & lag(Phase) == 2, PhaseLength +
lag(PhaseLength),
                       if_else(Phase == 3, PhaseLength, NULL)),
         Phase34 = if_else(Phase == 4, PhaseLength + lag(PhaseLength), NULL),
         Phase61 = if_else(Phase == 1, PhaseLength + lag(PhaseLength), NULL),
         Phase56 = if_else(Phase == 6, PhaseLength + lag(PhaseLength), NULL))
         #Phase23perc = if_else(Phase == 3, PhaseLengthPerc + lag(PhaseLengthPerc),
NULL),
         #Phase34perc = if_else(Phase == 4, PhaseLengthPerc + lag(PhaseLengthPerc),
NULL),
         #Phase61perc = if_else(Phase == 1, PhaseLengthPerc + lag(PhaseLengthPerc),
NULL),
         #Phase56perc = if_else(Phase == 6, PhaseLengthPerc + lag(PhaseLengthPerc),
NULL))

# Plot of mean jerk for each phase with the 1st stroke removed
#ggplot(data = filter(calc_by_stroke, Stroke != 1) %>%
#         mutate(Phase = paste("Phase", Phase)), aes(Stroke, Jerk, group = Phase)) +
#  geom_point() +
#  geom_smooth() +
#  facet_wrap(~Phase, ncol = 3, scales = "free") +
#  theme_minimal() +
#  theme(plot.title.position = "plot") +
#  labs(title = "Jerk for each Stroke separated by Phase",
#       y = "Jerk (m/s^-3)")

# Plot of stroke time for each phase with the 1st stroke removed
#ggplot(data = filter(calc_by_stroke, Stroke != 1) %>%
#         mutate(Phase = paste("Phase", Phase)), aes(Stroke, PhaseLength, group =
Phase)) +
#  geom_point() +
#  geom_smooth() +
#  facet_wrap(~Phase, ncol = 3, scales = "free") +
#  theme_minimal() +
#  theme(plot.title.position = "plot") +
#  labs(title = "Length of each Stroke separated by Phase",
#       y = "Time (s)")

# Plot of time for phases 2 & 3 with the 1st stroke removed
#ggplot(data = filter(calc_by_stroke, Stroke != 1), aes(Stroke, Phase23, group = Phase))
+
#  geom_point() +
#  geom_smooth() +
#  theme_minimal() +
#  theme(plot.title.position = "plot") +
#  labs(title = "Length of Phases 2 & 3 for each Stroke",
#       y = "Time (s)")
```

```
# Plot of time for phases 3 & 4 with the 1st stroke removed
#ggplot(data = filter(calc_by_stroke, Stroke != 1), aes(Stroke, Phase34, group = Phase))
+
#  geom_point() +
#  geom_smooth() +
#  theme_minimal() +
#  theme(plot.title.position = "plot") +
#  labs(title = "Length of Phases 3 & 4 for each Stroke",
#       y = "Time (s)")

# Plot of time for phases 6 to 1 with the 1st stroke removed
#ggplot(data = filter(calc_by_stroke, Stroke != 1), aes(Stroke, Phase61, group = Phase))
+
#  geom_point() +
#  geom_smooth() +
#  theme_minimal() +
#  theme(plot.title.position = "plot") +
#  labs(title = "Length of Phases 6 to 1 for each Stroke",
#       y = "Time (s)")

# Plot of velocity by phase for each stroke with 1st stroke removed
#ggplot(data = filter(calc_by_stroke, Stroke != 1), aes(Stroke, Velocity, group = Phase))
+
#  geom_point() +
#  geom_smooth() +
#  facet_wrap(~Phase, ncol = 3, scales = "free") +
#  theme_minimal() +
#  theme(plot.title.position = "plot") +
#  labs(title = "Mean Velocity by Phase for each Stroke",
#       y = "Velocity (m/s)")

# Calculations of mean & SD for phase time, jerk and time for phases 2 & 3, 3 & 4 and
6 to 1 for the piece
calc_by_piece <- calc_by_stroke %>%
  filter(Stroke != 1) %>%
  group_by(Phase) %>%
  summarise(Strokes = max(Stroke),
            Mean_PhaseLength = mean(PhaseLength, na.rm = T),
            SD_PhaseLength = sd(PhaseLength, na.rm = T),
            Mean_Jerk = mean(Jerk, na.rm = T),
            SD_Jerk = sd(Jerk, na.rm = T),
            Mean_Velocity = mean(Velocity, na.rm = T),
            SD_Velocity = sd(Velocity, na.rm = T),
            Mean_Phase23 = mean(Phase23, na.rm = T),
            SD_Phase23 = sd(Phase23, na.rm = T),
            Mean_Phase34 = mean(Phase34, na.rm = T),
            SD_Phase34 = sd(Phase34, na.rm = T),
            Mean_Phase61 = mean(Phase61, na.rm = T),
            SD_Phase61 = sd(Phase61, na.rm = T))
```

```
mean_stroke_vel <- filter6 %>%
  group_by(Stroke) %>%
  summarise(MeanStrokeVelocity = mean(as.numeric(`V(Acc)`, na.rm = T)))

calc_by_stroke <- left_join(calc_by_stroke, mean_stroke_vel, by = "Stroke")

# Calculation of time where acceleration is >= 0 for each stroke
time_above_stroke <- filter6 %>%
  group_by(Stroke) %>%
  mutate(Above = if_else(Filtered >= 0, 1 ,0)) %>%
  summarise(TimeAboveZeroAcc = sum(Above)*0.01)

# Plot for percentage of time where acceleration is >= 0 for each stroke
#ggplot(time_above_stroke, aes(Stroke, TimeAboveZeroAcc)) +
#  geom_point() +
#  geom_smooth() +
#  theme_minimal() +
#  theme(plot.title.position = "plot") +
#  labs(title = "Percentage of Stroke with Acceleration >= 0 m/s",
#       y = "Percentage of Stroke")

# Calculationof time where acceleration is <= 0 for each stroke
time_below_stroke <- filter6 %>%
  group_by(Stroke) %>%
  mutate(Below = if_else(Filtered < 0, 1, 0)) %>%
  summarise(TimeBelowZeroAcc = sum(Below)*0.01)

# Plot for percentage of time where acceleration is >= 0 for each stroke
#ggplot(time_below_stroke, aes(Stroke, TimeBelowZeroAcc)) +
#  geom_point() +
#  geom_smooth() +
#  theme_minimal() +
#  theme(plot.title.position = "plot") +
#  labs(title = "Percentage of Stroke with Acceleration < 0 m/s",
#       y = "Percentage of Stroke")

# Estimated area under the curve for each stroke where acceleration >= 0
auc_est <- filter6 %>%
  group_by(Stroke) %>%
  mutate(Above = if_else(Filtered >= 0, Filtered * 0.01, 0)) %>%
  summarise(AreaUnderCurve = sum(Above))

# Estimated area under the curve for each stroke where acceleration >= 0
#ggplot(auc_est, aes(Stroke, AUC)) +
#  geom_point() +
#  geom_smooth() +
#  theme_minimal()

# Magnitude of acceleration at each phase marker
```

```
accel_magnitude <- filter6 %>%
  select(Time, Filtered, Stroke, Phase) %>%
  group_by(Stroke, Phase) %>%
  slice(1)

# Magnitude of acceleration at each phase marker - wide format (no time marker)
accel_magnitude_wide <- accel_magnitude %>%
  pivot_wider(id_cols = 3, names_from = Phase, names_prefix = "Phase", values_from
= Filtered)

# Calculation of stroke rate
StrokeRate <-calc_by_stroke %>%
  group_by(Stroke) %>%
  summarise(StrokeRate = 60/(sum(PhaseLength)))

#Calcculation of stroke time
StrokeTime <- calc_by_stroke %>%
  group_by(Stroke) %>%
  summarise(StrokeTime = sum(PhaseLength))

#Adding ID variables
calc_by_stroke['BoatID']='JaMeM1x'
calc_by_stroke['Gender']='M'
calc_by_stroke['BoatClass']='1x'
calc_by_stroke['Race']='Heat'
calc_by_stroke['Date']='07/02/2020'
calc_by_stroke['Event']='NSWSC20'
calc_by_stroke <- calc_by_stroke[c(11, 12, 13, 14, 15, 16, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10)]

all_output <- left_join(calc_by_stroke, accel_magnitude, by = c("Stroke", "Phase"))
%>%
  left_join(., StrokeRate, by = c("Stroke")) %>%
  left_join(., StrokeTime, by = c("Stroke")) %>%
  left_join(., auc_est, by = c("Stroke")) %>%
  left_join(., time_above_stroke, by = c("Stroke"))%>%
  left_join(., time_below_stroke, by = c("Stroke"))

#Plots for anomalies #scales = "free_y" -- add after ncol = 1, to rescale y axis to data
variability
ggplot(all_output, aes(Stroke, StrokeTime))+
  geom_point()

ggplot(all_output, aes(Stroke, PhaseLength))+
  geom_point() +
  facet_wrap(~Phase, ncol = 1,)

ggplot(all_output, aes(Stroke, Jerk))+
  geom_point() +
  facet_wrap(~Phase, ncol = 1,)
```

```
ggplot(all_output, aes(Stroke, Velocity))+
  geom_point() +
  facet_wrap(~Phase, ncol = 1,)

ggplot(all_output, aes(Stroke, Filtered))+
  geom_point() +
  facet_wrap(~Phase, ncol = 1,)

ggplot(all_output, aes(Stroke, Phase23))+
  geom_point()

ggplot(all_output, aes(Stroke, Phase34))+
  geom_point()

ggplot(all_output, aes(Stroke, Phase61))+
  geom_point()

ggplot(all_output, aes(Stroke, Phase56))+
  geom_point()

ggplot(all_output, aes(Stroke, MeanStrokeVelocity))+
  geom_point()

ggplot(all_output, aes(Stroke, StrokeRate))+
  geom_point()

ggplot(all_output, aes(Stroke, AreaUnderCurve))+
  geom_point()

ggplot(all_output, aes(Stroke, TimeAboveZeroAcc))+
  geom_point()

ggplot(all_output, aes(Stroke, TimeBelowZeroAcc))+
  geom_point()

#Replace NAs with blank cells
all_output[is.na(all_output)] = ""

# Write the wide format df to a csv
write.csv(all_output, "C:/Users/ana.holt/OneDrive/PhD/Study 6_Acceleration curve
anaysis/Data processing/R processed files/Updated to remove anomalies_July20/.csv",
row.names = F)
```

Appendix Y: Study Five statistical analysis SAS script

```
*ex predict speed with power boatpred 23April20.sas;
/*
FILENAME REFFILE '/folders/myshortcuts/ExternalFiles/Projects/_VU
Melbourne/Ana Holt/Study 3/Complete_S6_Database_V6.xlsx';
libname ss '/folders/myshortcuts/ExternalFiles/Projects/_VU Melbourne/Ana
Holt/Study 3';
PROC IMPORT DATAFILE=REFFILE
	DBMS=XLSX
	OUT=ss.phasestudy3 replace;
	GETNAMES=YES;
  attrib _character_ _numeric_ label="";
RUN;
*/
libname ss '/folders/myshortcuts/ExternalFiles/Projects/_VU Melbourne/Ana
Holt/Study 3';

%macro anaboat;
data _null_;
if &logflag then call symput('unitsrawlog',"percent");
else call symput('unitsrawlog',"raw");
run;

data dat1;
set ss.phasestudy3;
if &predboat ne .;
attrib _character_ _numeric_ label="";
array a Jerk--Time StrokeRate--StrokeRatePeach;
if Missing=1 then do over a;
  a=.; Filtered=.;
  PhaseLength=.;
  end;
output;
if Phase=3 and lag(Phase)=1 then do;
  Phase=2;
  PhaseLength=0;
  do over a;
    a=.;
    end;
  output;
  end;

proc sort data=dat1;
by Gender BoatClass BoatID date race descending Stroke descending Phase;

data dat1a;
set dat1;
lagvel=lag(MeanStrokeVelocity);
```

```
if ("&predboat"="Jerk" or "&predboat"="PhaseLength") and Phase=6 then
MeanStrokeVelocity=lagvel;
drop lagvel;

proc sort;
by Gender BoatClass BoatID date race Stroke Phase;

*proc print data=dat1a(obs=20);
run;

data dat2;
set dat1a;
if Phase=3 and lag(PhaseLength)=0 then Filtered=.;
retain StrokeSet 0;
if lag(Date) ne Date or lag(Race) ne Race or lag(BoatID) ne BoatID then
StrokeSet=StrokeSet+1;
if "&predboat"="Jerk" or "&predboat"="PhaseLength" or "&predboat"="Filtered" then
if Phase=&phase;
if "&predboat"="TimeAboveZero" or "&predboat"="TimeBelowZero" or
"&predboat"="AreaUnderCurve" then if Phase=1;
rename Stroke=StrokeNo PowerTotal=PowerPeach MeanStrokeVelocity=AvBoatVel;
if Stroke>10;
if Phase=2 and "&predboat"="PhaseLength" and PhaseLength=0 then do;
  flag2=1;
  PhaseLength=.;
  end;
run;

*proc print data=dat2(obs=30);run;

data dat3;
set dat2;
if &predadjust ne .;
lag1=lag1(&predboat); lagb1=lag1(BoatID); lagr1=lag1(Race); lagd1=lag1(Date);
lag2=lag2(&predboat); lagb2=lag2(BoatID); lagr2=lag2(Race); lagd2=lag2(Date);
lag3=lag3(&predboat); lagb3=lag3(BoatID); lagr3=lag3(Race); lagd3=lag3(Date);
lag4=lag4(&predboat); lagb4=lag4(BoatID); lagr4=lag4(Race); lagd4=lag4(Date);
lag5=lag5(&predboat); lagb5=lag5(BoatID); lagr5=lag5(Race); lagd5=lag5(Date);
lag6=lag6(&predboat); lagb6=lag6(BoatID); lagr6=lag6(Race); lagd6=lag6(Date);
lag7=lag7(&predboat); lagb7=lag7(BoatID); lagr7=lag7(Race); lagd7=lag7(Date);
lag8=lag8(&predboat); lagb8=lag8(BoatID); lagr8=lag8(Race); lagd8=lag8(Date);
lag9=lag9(&predboat); lagb9=lag9(BoatID); lagr9=lag9(Race); lagd9=lag9(Date);
lag10=lag10(&predboat); lagb10=lag10(BoatID); lagr10=lag10(Race);
lagd10=lag10(Date);
lag11=lag11(&predboat); lagb11=lag11(BoatID); lagr11=lag11(Race);
lagd11=lag11(Date);
lag12=lag12(&predboat); lagb12=lag12(BoatID); lagr12=lag12(Race);
lagd12=lag12(Date);
lag13=lag13(&predboat); lagb13=lag13(BoatID); lagr13=lag13(Race);
lagd13=lag13(Date);
```

```
lag14=lag14(&predboat); lagb14=lag14(BoatID); lagr14=lag14(Race);
lagd14=lag14(Date);
lag15=lag15(&predboat); lagb15=lag15(BoatID); lagr15=lag15(Race);
lagd15=lag15(Date);
lag16=lag16(&predboat); lagb16=lag16(BoatID); lagr16=lag16(Race);
lagd16=lag16(Date);
lag17=lag17(&predboat); lagb17=lag17(BoatID); lagr17=lag17(Race);
lagd17=lag17(Date);
lag18=lag18(&predboat); lagb18=lag18(BoatID); lagr18=lag18(Race);
lagd18=lag18(Date);
lag19=lag19(&predboat); lagb19=lag19(BoatID); lagr19=lag19(Race);
lagd19=lag19(Date);
lag20=lag20(&predboat); lagb20=lag20(BoatID); lagr20=lag20(Race);
lagd20=lag20(Date);
lag21=lag21(&predboat); lagb21=lag21(BoatID); lagr21=lag21(Race);
lagd21=lag21(Date);
lag22=lag22(&predboat); lagb22=lag22(BoatID); lagr22=lag22(Race);
lagd22=lag22(Date);
lag23=lag23(&predboat); lagb23=lag23(BoatID); lagr23=lag23(Race);
lagd23=lag23(Date);
lag24=lag24(&predboat); lagb24=lag24(BoatID); lagr24=lag24(Race);
lagd24=lag24(Date);
lag25=lag25(&predboat); lagb25=lag25(BoatID); lagr25=lag25(Race);
lagd25=lag25(Date);
lag26=lag26(&predboat); lagb26=lag26(BoatID); lagr26=lag26(Race);
lagd26=lag26(Date);
lag27=lag27(&predboat); lagb27=lag27(BoatID); lagr27=lag27(Race);
lagd27=lag27(Date);
lag28=lag28(&predboat); lagb28=lag28(BoatID); lagr28=lag28(Race);
lagd28=lag28(Date);
lag29=lag29(&predboat); lagb29=lag29(BoatID); lagr29=lag29(Race);
lagd29=lag29(Date);
lag30=lag30(&predboat); lagb30=lag30(BoatID); lagr30=lag30(Race);
lagd30=lag30(Date);
array a lag1-lag30;
array b lagb1-lagb30;
array r lagr1-lagr30;
array d lagd1-lagd30;
do i=1 to 30;
  if b(i) ne BoatID or r(i) ne Race or d(i) ne Date then a(i)=.;
  end;
drop i lagb1-lagb30 lagr1-lagr30 lagd1-lagd30;
run;

proc sort data=dat3;
by Gender BoatClass BoatID date race descending StrokeNo;

data dat4;
set dat3;
retain rStrokeNo;
```

```
if lag(StrokeNo)<StrokeNo then rStrokeNo=0;
rStrokeNo=rStrokeNo+1;
if rStrokeNo>10;
rlag1=lag1(&predboat); lagb1=lag1(BoatID); lagr1=lag1(Race); lagd1=lag1(Date);
rlag2=lag2(&predboat); lagb2=lag2(BoatID); lagr2=lag2(Race); lagd2=lag2(Date);
rlag3=lag3(&predboat); lagb3=lag3(BoatID); lagr3=lag3(Race); lagd3=lag3(Date);
rlag4=lag4(&predboat); lagb4=lag4(BoatID); lagr4=lag4(Race); lagd4=lag4(Date);
rlag5=lag5(&predboat); lagb5=lag5(BoatID); lagr5=lag5(Race); lagd5=lag5(Date);
rlag6=lag6(&predboat); lagb6=lag6(BoatID); lagr6=lag6(Race); lagd6=lag6(Date);
rlag7=lag7(&predboat); lagb7=lag7(BoatID); lagr7=lag7(Race); lagd7=lag7(Date);
rlag8=lag8(&predboat); lagb8=lag8(BoatID); lagr8=lag8(Race); lagd8=lag8(Date);
rlag9=lag9(&predboat); lagb9=lag9(BoatID); lagr9=lag9(Race); lagd9=lag9(Date);
rlag10=lag10(&predboat); lagb10=lag10(BoatID); lagr10=lag10(Race);
lagd10=lag10(Date);
rlag11=lag11(&predboat); lagb11=lag11(BoatID); lagr11=lag11(Race);
lagd11=lag11(Date);
rlag12=lag12(&predboat); lagb12=lag12(BoatID); lagr12=lag12(Race);
lagd12=lag12(Date);
rlag13=lag13(&predboat); lagb13=lag13(BoatID); lagr13=lag13(Race);
lagd13=lag13(Date);
rlag14=lag14(&predboat); lagb14=lag14(BoatID); lagr14=lag14(Race);
lagd14=lag14(Date);
rlag15=lag15(&predboat); lagb15=lag15(BoatID); lagr15=lag15(Race);
lagd15=lag15(Date);
rlag16=lag16(&predboat); lagb16=lag16(BoatID); lagr16=lag16(Race);
lagd16=lag16(Date);
rlag17=lag17(&predboat); lagb17=lag17(BoatID); lagr17=lag17(Race);
lagd17=lag17(Date);
rlag18=lag18(&predboat); lagb18=lag18(BoatID); lagr18=lag18(Race);
lagd18=lag18(Date);
rlag19=lag19(&predboat); lagb19=lag19(BoatID); lagr19=lag19(Race);
lagd19=lag19(Date);
rlag20=lag20(&predboat); lagb20=lag20(BoatID); lagr20=lag20(Race);
lagd20=lag20(Date);
rlag21=lag21(&predboat); lagb21=lag21(BoatID); lagr21=lag21(Race);
lagd21=lag21(Date);
rlag22=lag22(&predboat); lagb22=lag22(BoatID); lagr22=lag22(Race);
lagd22=lag22(Date);
rlag23=lag23(&predboat); lagb23=lag23(BoatID); lagr23=lag23(Race);
lagd23=lag23(Date);
rlag24=lag24(&predboat); lagb24=lag24(BoatID); lagr24=lag24(Race);
lagd24=lag24(Date);
rlag25=lag25(&predboat); lagb25=lag25(BoatID); lagr25=lag25(Race);
lagd25=lag25(Date);
rlag26=lag26(&predboat); lagb26=lag26(BoatID); lagr26=lag26(Race);
lagd26=lag26(Date);
rlag27=lag27(&predboat); lagb27=lag27(BoatID); lagr27=lag27(Race);
lagd27=lag27(Date);
rlag28=lag28(&predboat); lagb28=lag28(BoatID); lagr28=lag28(Race);
lagd28=lag28(Date);
```

```
rlag29=lag29(&predboat); lagb29=lag29(BoatID); lagr29=lag29(Race);
lagd29=lag29(Date);
rlag30=lag30(&predboat); lagb30=lag30(BoatID); lagr30=lag30(Race);
lagd30=lag30(Date);
array a rlag1-rlag30;
array b lagb1-lagb30;
array r lagr1-lagr30;
array d lagd1-lagd30;
do i=1 to 30;
  if b(i) ne BoatID or r(i) ne Race or d(i) ne Date then a(i)=.;
  end;
drop i lagb1-lagb30 lagr1-lagr30 lagd1-lagd30;
run;

/*
proc print data=dat4(obs=300);
var BoatID date race rlagd1-rlagd10 rlagr1-rlagr10 phase rlagb1-rlagb10 StrokeNo
rStrokeNo &predboat rlag1-rlag10;
format Date date9.;
run;
*/
proc sort data=dat4;
by Gender BoatClass BoatID date race StrokeNo;

data dat4a;
set dat4;
RunMean&predboat=mean(of lag1-lag30, of rlag1-rlag30);
RunSD&predboat=std(of lag1-lag30, of rlag1-rlag30);
*RunMean&predboat=mean(lag1,lag2,lag3,lag4,lag5,lag6,lag7,lag8,lag9,lag10,rlag1,rla
g2,rlag3,rlag4,rlag5,rlag6,rlag7,rlag8,rlag9,rlag10);
*RunSD&predboat=std(lag1,lag2,lag3,lag4,lag5,lag6,lag7,lag8,lag9,lag10,rlag1,rlag2,rl
ag3,rlag4,rlag5,rlag6,rlag7,rlag8,rlag9,rlag10);
tValue=(&predboat-RunMean&predboat)/RunSD&predboat;
run;

data outliers1;
set dat4a;
if abs(tValue)>&tvalue;
run;

data dat5;
set dat4a;
if abs(tValue)>&tvalue then &predboat=.;
*if abs(tValue)>&tvalue and Phase=2 and &predboat ne 0 then &predboat=.;
run;

*second pass with outliers set to missing;
data dat6;
set dat5;
lag1=lag1(&predboat); lagb1=lag1(BoatID); lagr1=lag1(Race); lagd1=lag1(Date);
```

```
lag2=lag2(&predboat); lagb2=lag2(BoatID); lagr2=lag2(Race); lagd2=lag2(Date);
lag3=lag3(&predboat); lagb3=lag3(BoatID); lagr3=lag3(Race); lagd3=lag3(Date);
lag4=lag4(&predboat); lagb4=lag4(BoatID); lagr4=lag4(Race); lagd4=lag4(Date);
lag5=lag5(&predboat); lagb5=lag5(BoatID); lagr5=lag5(Race); lagd5=lag5(Date);
lag6=lag6(&predboat); lagb6=lag6(BoatID); lagr6=lag6(Race); lagd6=lag6(Date);
lag7=lag7(&predboat); lagb7=lag7(BoatID); lagr7=lag7(Race); lagd7=lag7(Date);
lag8=lag8(&predboat); lagb8=lag8(BoatID); lagr8=lag8(Race); lagd8=lag8(Date);
lag9=lag9(&predboat); lagb9=lag9(BoatID); lagr9=lag9(Race); lagd9=lag9(Date);
lag10=lag10(&predboat); lagb10=lag10(BoatID); lagr10=lag10(Race);
lagd10=lag10(Date);
lag11=lag11(&predboat); lagb11=lag11(BoatID); lagr11=lag11(Race);
lagd11=lag11(Date);
lag12=lag12(&predboat); lagb12=lag12(BoatID); lagr12=lag12(Race);
lagd12=lag12(Date);
lag13=lag13(&predboat); lagb13=lag13(BoatID); lagr13=lag13(Race);
lagd13=lag13(Date);
lag14=lag14(&predboat); lagb14=lag14(BoatID); lagr14=lag14(Race);
lagd14=lag14(Date);
lag15=lag15(&predboat); lagb15=lag15(BoatID); lagr15=lag15(Race);
lagd15=lag15(Date);
lag16=lag16(&predboat); lagb16=lag16(BoatID); lagr16=lag16(Race);
lagd16=lag16(Date);
lag17=lag17(&predboat); lagb17=lag17(BoatID); lagr17=lag17(Race);
lagd17=lag17(Date);
lag18=lag18(&predboat); lagb18=lag18(BoatID); lagr18=lag18(Race);
lagd18=lag18(Date);
lag19=lag19(&predboat); lagb19=lag19(BoatID); lagr19=lag19(Race);
lagd19=lag19(Date);
lag20=lag20(&predboat); lagb20=lag20(BoatID); lagr20=lag20(Race);
lagd20=lag20(Date);
lag21=lag21(&predboat); lagb21=lag21(BoatID); lagr21=lag21(Race);
lagd21=lag21(Date);
lag22=lag22(&predboat); lagb22=lag22(BoatID); lagr22=lag22(Race);
lagd22=lag22(Date);
lag23=lag23(&predboat); lagb23=lag23(BoatID); lagr23=lag23(Race);
lagd23=lag23(Date);
lag24=lag24(&predboat); lagb24=lag24(BoatID); lagr24=lag24(Race);
lagd24=lag24(Date);
lag25=lag25(&predboat); lagb25=lag25(BoatID); lagr25=lag25(Race);
lagd25=lag25(Date);
lag26=lag26(&predboat); lagb26=lag26(BoatID); lagr26=lag26(Race);
lagd26=lag26(Date);
lag27=lag27(&predboat); lagb27=lag27(BoatID); lagr27=lag27(Race);
lagd27=lag27(Date);
lag28=lag28(&predboat); lagb28=lag28(BoatID); lagr28=lag28(Race);
lagd28=lag28(Date);
lag29=lag29(&predboat); lagb29=lag29(BoatID); lagr29=lag29(Race);
lagd29=lag29(Date);
lag30=lag30(&predboat); lagb30=lag30(BoatID); lagr30=lag30(Race);
lagd30=lag30(Date);
```

```
array a lag1-lag30;
array b lagb1-lagb30;
array r lagr1-lagr30;
array d lagd1-lagd30;
do i=1 to 30;
  if b(i) ne BoatID or r(i) ne Race or d(i) ne Date then a(i)=.;
  end;
drop i lagb1-lagb30 lagr1-lagr30 lagd1-lagd30;
run;

proc sort data=dat6;
by Gender BoatClass BoatID date race descending StrokeNo;

data dat7;
set dat6;
*retain rStrokeNo;
*if lag(StrokeNo)<StrokeNo then rStrokeNo=0;
*rStrokeNo=rStrokeNo+1;
*if rStrokeNo>10;
rlag1=lag1(&predboat); lagb1=lag1(BoatID); lagr1=lag1(Race); lagd1=lag1(Date);
rlag2=lag2(&predboat); lagb2=lag2(BoatID); lagr2=lag2(Race); lagd2=lag2(Date);
rlag3=lag3(&predboat); lagb3=lag3(BoatID); lagr3=lag3(Race); lagd3=lag3(Date);
rlag4=lag4(&predboat); lagb4=lag4(BoatID); lagr4=lag4(Race); lagd4=lag4(Date);
rlag5=lag5(&predboat); lagb5=lag5(BoatID); lagr5=lag5(Race); lagd5=lag5(Date);
rlag6=lag6(&predboat); lagb6=lag6(BoatID); lagr6=lag6(Race); lagd6=lag6(Date);
rlag7=lag7(&predboat); lagb7=lag7(BoatID); lagr7=lag7(Race); lagd7=lag7(Date);
rlag8=lag8(&predboat); lagb8=lag8(BoatID); lagr8=lag8(Race); lagd8=lag8(Date);
rlag9=lag9(&predboat); lagb9=lag9(BoatID); lagr9=lag9(Race); lagd9=lag9(Date);
rlag10=lag10(&predboat); lagb10=lag10(BoatID); lagr10=lag10(Race);
lagd10=lag10(Date);
rlag11=lag11(&predboat); lagb11=lag11(BoatID); lagr11=lag11(Race);
lagd11=lag11(Date);
rlag12=lag12(&predboat); lagb12=lag12(BoatID); lagr12=lag12(Race);
lagd12=lag12(Date);
rlag13=lag13(&predboat); lagb13=lag13(BoatID); lagr13=lag13(Race);
lagd13=lag13(Date);
rlag14=lag14(&predboat); lagb14=lag14(BoatID); lagr14=lag14(Race);
lagd14=lag14(Date);
rlag15=lag15(&predboat); lagb15=lag15(BoatID); lagr15=lag15(Race);
lagd15=lag15(Date);
rlag16=lag16(&predboat); lagb16=lag16(BoatID); lagr16=lag16(Race);
lagd16=lag16(Date);
rlag17=lag17(&predboat); lagb17=lag17(BoatID); lagr17=lag17(Race);
lagd17=lag17(Date);
rlag18=lag18(&predboat); lagb18=lag18(BoatID); lagr18=lag18(Race);
lagd18=lag18(Date);
rlag19=lag19(&predboat); lagb19=lag19(BoatID); lagr19=lag19(Race);
lagd19=lag19(Date);
rlag20=lag20(&predboat); lagb20=lag20(BoatID); lagr20=lag20(Race);
lagd20=lag20(Date);
```

```
rlag21=lag21(&predboat); lagb21=lag21(BoatID); lagr21=lag21(Race);
lagd21=lag21(Date);
rlag22=lag22(&predboat); lagb22=lag22(BoatID); lagr22=lag22(Race);
lagd22=lag22(Date);
rlag23=lag23(&predboat); lagb23=lag23(BoatID); lagr23=lag23(Race);
lagd23=lag23(Date);
rlag24=lag24(&predboat); lagb24=lag24(BoatID); lagr24=lag24(Race);
lagd24=lag24(Date);
rlag25=lag25(&predboat); lagb25=lag25(BoatID); lagr25=lag25(Race);
lagd25=lag25(Date);
rlag26=lag26(&predboat); lagb26=lag26(BoatID); lagr26=lag26(Race);
lagd26=lag26(Date);
rlag27=lag27(&predboat); lagb27=lag27(BoatID); lagr27=lag27(Race);
lagd27=lag27(Date);
rlag28=lag28(&predboat); lagb28=lag28(BoatID); lagr28=lag28(Race);
lagd28=lag28(Date);
rlag29=lag29(&predboat); lagb29=lag29(BoatID); lagr29=lag29(Race);
lagd29=lag29(Date);
rlag30=lag30(&predboat); lagb30=lag30(BoatID); lagr30=lag30(Race);
lagd30=lag30(Date);
array a rlag1-rlag30;
array b lagb1-lagb30;
array r lagr1-lagr30;
array d lagd1-lagd30;
do i=1 to 30;
  if b(i) ne BoatID or r(i) ne Race or d(i) ne Date then a(i)=.;
  end;
drop i lagb1-lagb30 lagr1-lagr30 lagd1-lagd30;
run;

proc sort data=dat7;
by Gender BoatClass BoatID date race StrokeNo;

data dat7a;
set dat7;
RunMean&predboat=mean(of lag1-lag30, of rlag1-rlag30);
RunSD&predboat=std(of lag1-lag30, of rlag1-rlag30);
tValue=(&predboat-RunMean&predboat)/RunSD&predboat;
*if abs(tValue)>&tvalue then &predboat=.;
if flag2 then &predboat=0;
run;

data dat8;
set dat7a;
if abs(tValue)>&tvalue then &predboat=.;

data outliers2;
set outliers1 dat7a;
if abs(tValue)>&tvalue;
```

```
proc sort;
by Gender BoatClass BoatID date race;
/*
title "Values of &predboat in Phase &phase with running tValue>&tvalue for up to 30
observations each side";
*title2 "First- AND second-pass outliers removed";
proc print data=outliers2;
var Gender BoatClass BoatID BoatID date race StrokeSet phase StrokeNo tValue
RunMean&predboat RunSD&predboat &predBoat;
format Date date9. tValue 5.1 RunMean&predboat RunSD&predboat 5.&decpredboat;
by Gender BoatClass BoatID;
*where abs(tValue)>&tvalue;
run;
*/
title "No. of non-missing and missing strokes for &predboat in Phase &phase";
title2 "N obs is the number of stroke sets";
proc means noprint data=dat8;
var &predboat;
*var AvBoatVel;
by Gender BoatClass BoatID date race;
*where Side="B";
output out=meansd n=NoNonmissing nmiss=NoMissing;

proc means sum mean min max maxdec=0 data=meansd;
var NoNonmissing NoMissing;
class Gender BoatClass;
run;

*start of the program for the mixed model;
*proc print data=dat8(obs=10);

data dat9;
set dat8;
drop lag1--RunSD&predboat;
&subset;
if BoatID="VBCVMHM2-" and StrokeSet=42 then delete;
*if Race="Trials" then Race="Final";
if &predboat=. then do;
  AvBoatVel=.;
  StrokeRate=.;
  PowerPeach=.;
  end;
*if Race="Rep" or Race="Semi" then Race="Heat";
run;

*proc sort data=dat9;
*by Gender BoatClass BoatID StrokeSet;

/*
ods graphics / reset width=20cm height=16cm imagemap attrpriority=none;
```

```
title "Scatterplot of PowerPeach vs StrokeNo for Phase=&phase";
title2 "First- and second-pass outliers removed";
proc sgplot data=dat9 uniform=scale;
styleattrs
  datacolors=(black blue red green pink greenyellow)
  datalinepatterns=(dot)
  datacontrastcolors=(black blue red green pink greenyellow)
  datasymbols=(circlefilled);
  *datasymbols=(circlefilled squarefilled diamondfilled trianglefilled);
*reg x=Vicon y=&dep/nomarkers name='def' group=DeviceUnit;
*reg x=Vicon1 y=Identity/nomarkers name='def' lineattrs=(color=black pattern=dash
thickness=0.5);
scatter x=StrokeNo y=PowerPeach/markerattrs=(size=5) filledoutlinedmarkers
name='abc' group=StrokeSet;
*scatter x=StrokeNo y=&dep/groupdisplay=cluster clusterwidth=0.3
markerattrs=(size=8) filledoutlinedmarkers group=DeviceUnit  name='abc';
*series x=&dep y=MeanLine /lineattrs=(pattern=dash thickness=1 color=black);
*keylegend 'def' /noborder titleattrs=(size=16) valueattrs=(size=16);
keylegend 'abc' /title="StrokeSet:" noborder titleattrs=(size=16) valueattrs=(size=16);
yaxis label="PowerPeach" labelpos=top labelattrs=(size=16) valueattrs=(size=16);
xaxis label="StrokeNo" labelattrs=(size=16) valueattrs=(size=16);
refline 10/axis=x lineattrs=(pattern=dot thickness=1 color=black);
*refline MeanDep/axis=x lineattrs=(pattern=dash thickness=0.25 color=black);
by Gender BoatClass BoatID;
*where Participant="VMTW2-";
*where StrokeNo>1; * and  Participant="VMTW2-";
where abs(tValue)<&tvalue;
run;
ods graphics/reset;
*/
data decodeset;
set dat9;
if lag(StrokeSet) ne StrokeSet;
keep Gender BoatClass StrokeSet Date Race BoatID;
run;

title "Within-boat simple stats for AvBoatVel (m/s)";
title2 "Nobs is the number of stroke sets";
proc means noprint data=dat9;
var AvBoatVel;
by Gender BoatClass BoatID StrokeSet;
*where Side="B";
output out=meansd n=NoOfObs nmiss=NoMissing mean=WthnBoatMean
std=WthnBoatSD;

proc means maxdec=0 sum;
var NoOfObs NoMissing;
class Gender BoatClass;
run;
```

```
proc means maxdec=2;
var WthnBoatMean WthnBoatSD;
class Gender BoatClass;
run;

title "Within-boat simple stats for &predadjust (raw)";
title2 "Nobs is the number of stroke sets";
proc means noprint data=dat9;
var &predadjust;
by Gender BoatClass BoatID StrokeSet;
*where Side="B";
output out=meansd mean=WthnBoatMean std=WthnBoatSD;

proc means maxdec=&decpredadjust;
var WthnBoatMean WthnBoatSD;
class Gender BoatClass;
run;

data dat10;
set dat9;
PowerCubRoot=PowerPeach**(1/3);
if &logflag then do;
  &dep=100*log(&dep);
  &predadjust=100*log(&predadjust);
  PowerCubRoot=100*log(PowerCubRoot);
  end;
if &logflagpred then &predboat=100*log(&predboat);
run;

*proc print data=dat3(obs=1000);
run;

title "Within-boat simple stats for log-transformed AvBoatVel";
title2 "Nobs is the number of stroke sets";
proc means noprint data=dat10;
var AvBoatVel;
by Gender BoatClass BoatID StrokeSet;
*where Side="B";
output out=meansd mean=WthnBoatMean std=WthnBoatSD;

proc means maxdec=1;
var WthnBoatMean WthnBoatSD;
class Gender BoatClass;
run;

title "Within-boat simple stats for log-transformed &predadjust";
title2 "Nobs is the number of stroke sets";
proc means noprint data=dat10;
var &predadjust;
by Gender BoatClass BoatID StrokeSet;
```

```
*where Side="B";
output out=meansd mean=WthnBoatMean std=WthnBoatSD;

proc means maxdec=1;
var WthnBoatMean WthnBoatSD;
class Gender BoatClass;
run;

title "Between- and within-boat simple stats for raw &predboat Phase=&phase";
title2 "Nobs is the number of boats";
proc means noprint data=dat9;
var &predboat;
by Gender BoatClass BoatID;
*where Side="B";
output out=predboatmean mean=&predboat.Mean std=WthnBoatSD;

data predboatmean1;
set predboatmean;
&predboat.MeanResc=&predboat.Mean;

proc standard data=predboatmean1 out=predboatmean2 mean=0 std=0.5;
var &predboat.MeanResc;
by Gender BoatClass;

proc means maxdec=&decpredboat;
var &predboat.Mean &predboat.MeanResc WthnBoatSD;
class Gender BoatClass;
run;

title "Between- and within-boat simple stats for log-transformed &predboat
Phase=&phase";
title2 "Nobs is the number of boats";
proc means noprint data=dat10;
var &predboat &dep &predadjust;
by Gender BoatClass BoatID;
*where Side="B";
output out=predboatmean mean=&predboat.Mean &dep.Mean &predadjust.Mean
std=WthnBoatSD;

data predboatmean1;
set predboatmean;
&predboat.MeanResc=&predboat.Mean;

proc standard data=predboatmean1 out=predboatmean2 mean=0 std=0.5;
var &predboat.MeanResc;
by Gender BoatClass;

proc means maxdec=&decpredboat;
var &predboat.Mean &predboat.MeanResc WthnBoatSD;
class Gender BoatClass;
```

```
where &logflagpred=1;
run;

title "Between-boat simple stats for log-transformed &dep.Mean and
&predadjust.Mean";
title2 "Compare the SDs: we expect SD for &predadjust to be more than 3x the SD for
AvBoatVel";
title3 "N is the number of boats";
proc means maxdec=1 data=predboatmean n mean std min max;
var &dep.Mean &predadjust.Mean;
class Gender BoatClass;
run;

data dat11;
merge dat10 predboatmean2(keep=Gender BoatClass BoatID &predboat.Mean
&predboat.MeanResc);
by Gender BoatClass BoatID;
run;

/*
title "Within-boat correlations";
ods select none;
proc corr data=dat5 nosimple outp=corrs;
var AvBoatVel &predadjust &predboat;
by Gender BoatClass BoatID StrokeSet;
*ods output FisherPearsonCorr=fish;
run;
ods select all;

*proc print data=corrs(obs=20);run;

data corrs1;
retain SortOrder;
set corrs;
if _Type_="CORR";
drop _type_ ;
if _name_ ne "";
if _name_="AvBoatVel" then SortOrder=0;
if lag(_name_) ne _name_ then SortOrder=SortOrder+1;
rename _name_=Predictor;
array a AvBoatVel &predadjust &predboat;
do over a;
  if a=1 then a=.;
  end;

proc sort;
by Gender BoatClass SortOrder Predictor;

proc means noprint;
var AvBoatVel &predadjust &predboat;
```

```
by Gender BoatClass SortOrder Predictor;
output out=corrs2 mean=;
run;

proc print noobs;
var Gender BoatClass Predictor AvBoatVel &predadjust &predboat;
by Gender BoatClass;
format _numeric_ 5.2;
run;
*/
/*
proc freq data=dat4;
tables Participant*Race/nocol norow nopercent nocum;
by Gender BoatClass;
run
*/
/*
proc print data=dat3; *(obs=10);
where BoatID ne "VRMLM1x";
run;
*/
/*
data pdata;
Gender="M"; BoatClass="1x";
estimate=6;output;estimate=2;output; output;
estimate=9;output;estimate=5;output;estimate=10;output;estimate=6;output;
do i=1 to 6;
  estimate=5;
  output;
  end;
Gender="M"; BoatClass="2-";
do i=1 to 7;
  estimate=5;
  output;
  end;
Gender="W"; BoatClass="1x";
do i=1 to 10;
  estimate=5;
  output;
  end;
Gender="W"; BoatClass="2-";
do i=1 to 13;
  estimate=5;
  output;
  end;
keep Gender BoatClass estimate;
*/
/*
proc univariate plot data=dat4;
var DriveAccelMax;
```

```
class Participant;
by Gender Boatclass;
run;
*/
/*
proc sort data=dat4;
by Gender BoatClass Participant Side;

proc standard data=dat4 mean=0 out=dat5;
var &pred;
by Gender BoatClass Participant;
run;

title "100*log(&pred), simple stats with each participlant rescaled to zero";
proc means maxdec=0 data=dat5;
var &pred;
class Gender BoatClass;
run;
*/
*proc print data=dat5(obs=500);run;

proc standard data=dat11 out=dat12 mean=0;
var &predboat;
by Gender BoatClass BoatID;

proc standard data=dat12 out=dat13 std=0.5;
var &predboat;
by Gender BoatClass;
run;

proc standard data=dat13 out=dat14 mean=0;
var &predadjust;
by Gender BoatClass;
run;

/*
*check dataset;

proc means;
var &predboat;
by Gender BoatClass;
run;

*proc print data=dat7(obs=400);run;
proc freq data=dat7;
tables strokeset*BoatID/norow nocol nopercent;
by gender boatclass;
run;
*/
```

```
data cov lsm lsmdiff lsmdiff1 lsmdiff2  lsmest est solf solr pred pred1;

%let convcrit=CONVH=1E-8 convf=1E-8;

ods select none;
*ods listing close;
proc mixed data=dat14 covtest cl alpha=&alpha &nob &convcrit;
class BoatID Race StrokeSet Date;
*model &dep=&predadjust/outp=pred s residual ddfm=sat alphap=&alpha; *better
without ddfm=sat?;
model &dep=&predadjust &predboat/outp=pred s residual ddfm=sat alphap=&alpha
ddfm=sat; *better without ddfm=sat?;
*model &dep=&predadjust &predboat.MeanResc &predboat/outp=pred s residual
ddfm=sat alphap=&alpha ddfm=sat; *better without ddfm=sat?;
*model &dep=PowerCubRoot PowerCubRoot*PowerCubRoot/outp=pred s residual
ddfm=sat alphap=&alpha ddfm=sat; *better without ddfm=sat?;
estimate "Intercept" int 1/cl alpha=&alpha;
estimate "&predadjust /%" &predadjust 1/cl alpha=&alpha;
*estimate "PowerCubRoot /%" PowerCubRoot 1/cl alpha=&alpha;
*estimate "PowerCubRoot^2 /%^2" PowerCubRoot*PowerCubRoot 1/cl alpha=&alpha;
*estimate "&predboat.Mean 2SD" &predboat.MeanResc 1/cl alpha=&alpha;
estimate "&predboat 2SD" &predboat 1/cl alpha=&alpha;
*random int &predboat/subject=BoatID type=un s cl alpha=&alpha;
random int &predadjust/subject=BoatID s cl alpha=&alpha &type;
*random &predadjust/subject=BoatID s cl alpha=&alpha;
random &predboat/subject=BoatID s cl alpha=&alpha;
random StrokeSet/subject=BoatID s cl alpha=&alpha;
*random StrokeSet Date/s cl alpha=&alpha;
repeated/group=BoatID;
/*
lsmestimate Device*SerialNumber "NK-Vicon:" 0;
lsmestimate Device*SerialNumber
  "Unit 1100827" 1 0 0 0  0 0 0  0 0 0  -1 0 0 0,
  "Unit 1101134" 0 1 0 0  0 0 0  0 0 0  0 -1 0 0,
  "Unit 1101819" 0 0 1 0  0 0 0  0 0 0  0 0 -1 0,
  "Unit 1101823" 0 0 0 1  0 0 0  0 0 0  0 0 0 -1
  /cl alpha=0.1;
*/
&parms;
*parms 5 5  5 5 5 5 5 5 5 5 5 5 5;
*parms/pdata=pdata;
ods output classlevels=clev;
ods output covparms=cov;
ods output lsmeans=lsm;
ods output diffs=lsmdiff;
ods output estimates=est;
ods output solutionf=solf;
ods output solutionr=solr;
ods output lsmestimates=lsmest;
by Gender BoatClass;
```

```
*where Gender="W" and BoatClass="2-";
*where Gender="M" and BoatClass="1x";
run;
ods select all;

title1 "&dep in Phase &phase predicted by &predadjust &predboat in a log-log mixed
model";

title2 "Class levels; Race not currently in the model";
*title3 "StrokeSet=0 is for boat predicted means";
proc print data=clev noobs; run;

title2 "Random effects, to check on adequacy of the model";
proc print data=cov noobs;
by Gender BoatClass;
run;

*proc print data=clev;run;
*proc print data=cov;run;
*proc print data=est;run;
*by Gender Boatclass;
run;

*proc print data=cov;run;
/*
proc print data=clev;run;
proc print data=cov;run;
proc print data=est;run;

proc print data=lsm;run;
proc print data=solr;run;
proc print data=decodeset;run;
*by gender boatclass;
run;
*/

data pred1;
set pred;
if &logflag then do;
  *&pred=exp(&pred/100);
  &dep=exp(&dep/100);
  *pred=exp(pred/100);
  end;

*proc print data=pred;run;

*title2 "Residuals (log-transformed but not standardized) vs predicteds";
title2 "Standardized residuals vs predicteds";
options ls=80 ps=36;
proc plot data=pred1;
```

```
plot StudentResid*pred;
by Gender Boatclass;
run;
/*
*check some extreme or strange values;
data check;
set pred1(drop=lag1--RunSD&predboat);
*if Gender="M" and BoatClass="2-" and .<pred<140; *Ana to delete the last few
strokes;
*if Gender="W" and BoatClass="1x" and .<pred<120; *Ana done;
if Gender="W" and BoatClass="2-" and pred>170; *Ana done;

proc print;run;
*/
/*
proc sort data=pred1;
by Gender Boatclass StrokeSet;

ods graphics / reset width=12cm height=10cm imagemap attrpriority=none;
proc sgplot data=pred1; *uniform=all;
scatter x=pred y=Resid/markerattrs=(size=3 color=black symbol=circlefilled)
filledoutlinedmarkers MARKERFILLATTRS=(color=black);
*scatter x=StrokeNo y=Resid/markerattrs=(size=3 color=black symbol=circlefilled)
filledoutlinedmarkers MARKERFILLATTRS=(color=black);
refline 0/axis=y lineattrs=(pattern=dot thickness=1 color=blue);
by Gender Boatclass;
*where Gender="M" and BoatClass="2-" and StrokeSet=36;
run;
ods graphics / reset;
*/
/*
proc plot data=pred1;
plot (&dep &pred)*StrokeNo;
by Gender Boatclass StrokeSet Side;
where Gender="M" and BoatClass="2-" and StrokeSet=36;
run;

options ps=52 ls=100;
proc print data=pred1;
var Gender Boatclass BoatID Date Race StrokeSet StrokeNo AvBoatVel &dep  pred
resid Studentresid;
format &dep pred 5.&decdep studentresid 5.1;
by Gender Boatclass;
where Resid<-200;
*where Gender="M" and BoatClass="2-" and StrokeSet=36;
run;
*/
option ls=90;
options ls=100 ps=50;
data pred2;
```

```
set pred1;
if abs(StudentResid)>4.5;

options ps=52 ls=100;
proc print data=pred2;
var Gender Boatclass BoatID Date Race StrokeSet StrokeNo &dep &predboat pred
resid Studentresid;
title2 "Outliers (Standardized residual >4.5)";
format &dep 5.&decdep studentresid 5.1;
by Gender Boatclass;
run;
option ls=90;
/*
title2 "Top-left tail of residuals for Gender=M and BoatClass=2-";
proc print data=pred1;
where Gender="M" and BoatClass="2-" and .<pred<145;
var Gender Boatclass BoatID Date Race StrokeSet StrokeNo &dep &predboat pred
resid Studentresid;
format &dep 5.&decdep studentresid 5.1;
run;
*/

/*
title2 "Predicted mean power of boats at overall mean and max boat speed, no wind";
data pred1;
set pred;
if PredictAt ne "";
CLpm=(Upper-Lower)/2;
rename pred=PredictedPower;

proc sort data=pred1;
by descending PredictAt Gender BoatClass;

proc print data=pred1;
var PredictAt Gender BoatID BoatClass StrokeSet PredictAt Race AvBoatVel
PredictedPower CLpm DF      Alpha Lower   Upper;
format AvBoatVel 5.1 PredictedPower CLpm DF     Lower  Upper 5.0;
by descending PredictAt Gender BoatClass;
run;
*/

*thresholds via given smallest important;
data thresholds;
*set stdsd;
Units="Raw";
if &logflag then Units="%";
magnithresh=&MagniThresh;
if &logflag=0 then do; *these raw thresholds are actually via standardization;
Threshold="Small    "; DeltaMeanBene=magnithresh; DeltaMeanHarm=-magnithresh;
SDthreshold=abs(magnithresh)/2; output;
```

```
  Threshold="Moderate"; DeltaMeanBene=magnithresh*3; DeltaMeanHarm=-
magnithresh*3; SDthreshold=abs(DeltaMeanBene)/2; output;
  Threshold="Large"; DeltaMeanBene=magnithresh*6; DeltaMeanHarm=-
magnithresh*6; SDthreshold=abs(DeltaMeanBene)/2; output;
  Threshold="Vlarge"; DeltaMeanBene=magnithresh*10; DeltaMeanHarm=-
magnithresh*10; SDthreshold=abs(DeltaMeanBene)/2; output;
  Threshold="Xlarge"; DeltaMeanBene=magnithresh*20; DeltaMeanHarm=-
magnithresh*20; SDthreshold=abs(DeltaMeanBene)/2; output;
  end;
else do;
  magnithresh=100*log(1+magnithresh/100);
  Threshold="Small   "; DeltaMeanBene=100*exp(magnithresh/100)-100;
DeltaMeanHarm=100*exp(-magnithresh/100)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2)-100; output;
  Threshold="Moderate"; DeltaMeanBene=100*exp(magnithresh/100*3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*3)-100; output;
  Threshold="Large"; DeltaMeanBene=100*exp(magnithresh/100*1.6/0.3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*1.6/0.3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*1.6/0.3)-100; output;
  Threshold="Vlarge"; DeltaMeanBene=100*exp(magnithresh/100*2.5/0.3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*2.5/0.3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*2.5/0.3)-100; output;
  Threshold="Xlarge"; DeltaMeanBene=100*exp(magnithresh/100*4.0/0.3)-100;
DeltaMeanHarm=100*exp(-magnithresh/100*4.0/0.3)-100;
SDthreshold=100*exp(abs(magnithresh)/100/2*4.0/0.3)-100; output;
  end;

title2 "&dep magnitude thresholds (&unitsrawlog), based on a given smallest important
for means of &magnithresh (&unitsrawlog).";
title3 "Factors for the thresholds for moderate, large, v.large and x.large are .9/.3x,
1.6/.3x, 2.5/.3x and 4/.3x the smallest important,";
title4 "i.e., competitive athlete thresholds; thresholds for SDs are half those for means.";
proc print noobs;
var Threshold Units DeltaMeanBene DeltaMeanHarm SDthreshold;
format DeltaMeanBene DeltaMeanHarm SDthreshold 5.&decdep;
where &logflag=0;
run;

*make macro variables for magnitude thresholds for the MBD steps;
data _null_;
length ThreshX $ 9;
set thresholds;
if &logflag then Thresh=abs(100*log(1+DeltaMeanBene/100)); *convert back to log
value, could do it with DeltaMeanHarm;
else Thresh=abs(DeltaMeanBene);
ThreshX=trim(Threshold)||'X';
call symput(ThreshX,Thresh);

proc print noobs;
```

```
var Threshold Units DeltaMeanBene DeltaMeanHarm SDthreshold;
format DeltaMeanBene DeltaMeanHarm 5.&deceff SDthreshold 5.2;
where &logflag=1;
run;

data est1;
set est;
if estimate=0 then estimate=.;
array a estimate lower upper;
if &logflag=1 then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(upper-lower)/2;
*if index(Label,"RFDAv") and index(Label,BoatClass)=0 then delete;

title2 "Fixed effects (&unitsrawlog)";
title3 "Ignore the intercept; the &predadjust is the index in V=kP^x";
proc print data=est1 noobs;
var Gender Boatclass label Estimate  CLpm Lower Upper DF alpha;
format estimate CLpm lower upper 5.2;
by Gender Boatclass;
run;

title2 "MBD for fixed effects with a given smallest important for means of
&magnithresh (&unitsrawlog)";
data est1;
set est;
if index(Label,"2SD");
length Prob $ 8 Magni $ 4 QualMag $ 8;
QualMag="Trivial";
if abs(estimate)>&smallx then QualMag="Small";
if abs(estimate)>&moderatex then QualMag="Moderate";
if abs(estimate)>&largex then QualMag="Large";
if abs(estimate)>&vlargex then QualMag="Vlarge";
if abs(estimate)>&xlargex then QualMag="Xlarge";
MagniThresh=&MagniThresh;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh))/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh))/StdErr,DF);
if &LogFlag=1 then do;
  if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  else do;
    ChancePos=100*(1-ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  end;

ChanceTriv=100-ChancePos-ChanceNeg;
```

```
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
ClinFlag=1; *want inferences to be clinical;
*if index(label,"2SD") then ClinFlag=0; *covariates definitely need to be non-clinical;
*clinical inferences;
if clinflag then do;
Precision="unclear";
ChPos=ChancePos; ChNeg=ChanceNeg;
if MagniThresh<0 then do;
  ChPos=ChanceNeg; ChNeg=ChancePos;
  end;
if ChNeg<0.5 then do;
  Precision="@25/.5%";
  if ChNeg<0.1 then Precision="@5/.1% ";
  Magni="bene";
  if ChNeg<0.1 and ChPos>5 then Prob="unlikely";
  if ChPos>25 then Prob="possibly";
  if ChPos>75 then Prob="likely  ";
  if ChPos>95 then Prob="v.likely";
  if ChPos>99.5 then Prob="m.likely";
  if ChPos<25 and prob ne "unlikely" then do;
    Magni="triv";
    if ChanceTriv>25 then Prob="possibly";
    if ChanceTriv>75 then Prob="likely  ";
    if ChanceTriv>95 then Prob="v.likely";
    if ChanceTriv>99.5 then Prob="m.likely";
    end;
  end;
else do; *ChNeg>0.5;
  if ChPos<25 then do;
    Precision="@25/.5%";
    if ChPos<5 then Precision="@5/.1% ";
    if ChanceTriv>25 then do;
      Magni="triv";Prob="possibly";
      if ChanceTriv>75 then Prob="likely";
      if ChanceTriv>95 then Prob="v.likely";
      if ChanceTriv>99.5 then Prob="m.likely";
      end;
    if ChNeg>25 then do;
      Magni="harm";Prob="possibly";
      if ChNeg>75 then Prob="likely  ";
      if ChNeg>75 then Prob="likely  ";
      if ChNeg>95 then Prob="v.likely";
      if ChNeg>99.5 then Prob="m.likely";
      end;
    end;
  end;
if Precision="unclear" and
  (MagniThresh>0 and ORPosNeg>25/75/(0.5/99.5) or StdzedMagniThresh<0 and
ORNegPos>25/75/(0.5/99.5))
```

```
  then do;
  Precision="OR>66.3";
  Magni="bene";
  if ChPos>25 then Prob="possibly";
  if ChPos>75 then Prob="likely  ";
  if ChPos>95 then Prob="v.likely";
  if ChPos>99.5 then Prob="m.likely";
  end;
output;
end;
*mechanistic inferences;
ClinFlag=0;
Precision="unclear";
Prob="";
Magni="     ";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then Precision="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then Precision="@99%  ";
if Precision ne "unclear" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if Precision ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
*end;
output;

data est2;
set est1;
if estimate=0 or estimate=. then do;
  estimate=.; magnithresh=.; magni=""; Precision=""; Prob=""; Units=""; Magni="";
Precision=.; QualMag="";
  end;
array a estimate lower upper;
if &logflag then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(Upper-lower)/2;
rename df=DegFree;
if index(Label,".")=1 then Label=substr(Label,2);
run;
```

```
*options ls=135 ps=80;
title3 "Units for estimates, confidence limits and smallest important are &unitsrawlog";
title4 "Non-clinical inferences";
proc print data=est2 noobs;
where clinflag=0;
var Gender BoatClass label estimate CLpm lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos QualMag Prob Magni Precision;
format estimate CLpm lower upper MagniThresh 5.&deceff Probt best5. ChanceNeg
ChanceTriv
  ChancePos 5.1 DegFree 5.0;
*by Gender BoatClass;
run;

data covall;
*length Device $ 5 Group $ 12;
set cov;
if covparm ne "UN(2,1)";
alpha=&alpha;
DegFree=2*ZValue**2;
*if Lower=. then do;
  *Lower=DegFree*estimate/CINV(1-alpha/2,DegFree);
  *Upper=DegFree*estimate/CINV(alpha/2,DegFree);
  *conf limits via normal dist;
if StdErr ne 0 then do;
  lower=estimate+probit(alpha/2)*StdErr;
  upper=estimate-probit(alpha/2)*StdErr;
  end;
array a estimate lower upper;
do over a;
  a=sign(a)*sqrt(abs(a));
  end;
if &logflag=1 then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(upper-lower)/2;
*if substr(covparm,1,2) ne "UN" then CLpm=(upper-lower)/2;
CLtd=sqrt(upper/lower);
drop StdErr--ProbZ;
if covparm="UN(1,1)" then covparm="Intercept";
if covparm="UN(2,2)" then covparm="&predadjust";
Group=substr(Group,8);

title2 "Random effects as standard deviations (&unitsrawlog)";
title3 "Intercept is boat indiv differences in mean efficiency";
title4 "&predadjust is boat indiv differences in x, where V=kP^x";
title5 "&predboat is boat indiv differences in slope";
title6 "StrokeSet is boat mean differences between races, e.g., due to changes in
environment";
*title5 "Date is mean differences between dates, e.g., due to changes in environment";
```

```
title7 "Residual is the stroke to stroke variation in speed";
proc print noobs data=covall;
var Gender Boatclass covparm subject Group estimate CLpm lower upper alpha;
format estimate lower upper CLpm 5.&deceff CLtd 5.2 DegFree 5.0;
by Gender Boatclass;
run;
/*
proc print noobs data=covall;
var Gender Boatclass covparm subject Group estimate CLpm lower upper alpha;
format estimate lower upper CLpm 5.2 CLtd 5.2 DegFree 5.0;
*by Gender Boatclass;
where covparm="&predadjust";
run;
*/

title2 "Non-clinical MBD for random effects";
title3 "Magnithresh is half the given smallest difference of &magnithresh
(&unitsrawlog) for means";
title4 "&predboat is boat indiv differences in slope";
*title6 "Non-clinical MBD for SD representing random effects";
*title3 "Intercept is boat indiv differences in mean efficiency";
*title4 "StrokeSet is boat mean differences between races, e.g., due to changes in
environment";
*title5 "Date is mean differences between dates, e.g., due to changes in environment";
*title6 "Residual is the stroke to stroke variation in speed";
data cov1;
set cov;
if covparm="UN(1,1)" then covparm="Intercept";
if covparm="UN(2,2)" then covparm="&predadjust";
if covparm="&predboat";
*if substr(Group,8)="NK" or substr(Group,8)="Peach"; *add or modify, depending on
the analysis;
*lower=estimate+probit(alpha/2)*StdErr; *for those models where nobound did not
work;
*upper=estimate-probit(alpha/2)*StdErr;
QualMag="Trivial ";
if sqrt(abs(estimate))>&smallx/2 then QualMag="Small";
if sqrt(abs(estimate))>&moderatex/2 then QualMag="Moderate";
if sqrt(abs(estimate))>&largex/2 then QualMag="Large";
if sqrt(abs(estimate))>&vlargex/2 then QualMag="Vlarge";
if sqrt(abs(estimate))>&xlargex/2 then QualMag="Xlarge";
DF=999;
MagniThresh=abs(&MagniThresh)/2;
if &logflag then Magnithresh=100*exp(log(1+abs(&magnithresh)/100)/2)-100;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh)**2)/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh)**2)/StdErr,DF);
if &logflag then do;
  *if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-
(100*log(1+MagniThresh/100))**2)/StdErr,DF));
```

```
    ChanceNeg=100*ProbT(-(estimate+(100*log(1+MagniThresh/100))**2)/StdErr,DF);
    end;
ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
*ClinFlag=0; *want all inferences to be non-clinical for within-subject random effect;
*mechanistic inferences;
Precision="unclear";
Prob="        ";
Magni="     ";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then Precision="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then Precision="@99%  ";
if Precision ne "unclear" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if Precision ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
if not stderr then do; Magni="";Precision=""; end;
Group=substr(Group,8);

data cov2;
set cov1;
alpha=&alpha;
*if covparm ne "Residual" then do;
  lower=estimate+probit(alpha/2)*StdErr;
  upper=estimate-probit(alpha/2)*StdErr;
*  end;
array a estimate lower upper;
do over a;
  a=sign(a)*sqrt(abs(a));
  end;
DegFree=2*Zvalue**2;
array r SD lower upper;
if &logflag=1 then do over r;
  r=100*exp(r/100)-100;
  end;
CLpm=(upper-lower)/2;
*if substr(covparm,1,2) ne "UN" then CLpm=(upper-lower)/2;
CLtd=sqrt(upper/lower);
```

```
run;

title6 "Non-clinical MBD for SD representing random effects";
title7 "Magnithresh is half the given smallest difference for means";
proc print data=cov2 noobs;
var Gender Boatclass covparm Subject Group estimate CLpm lower upper alpha
  MagniThresh ChanceNeg ChanceTriv ChancePos QualMag Prob Magni Precision;
format estimate CLpm lower upper 5.&deceff MagniThresh 5.2 ChanceNeg ChanceTriv
  ChancePos 5.1 DF 5.0;
*by Gender Boatclass;
run;

*proc print data=solr;run;
*random-effect solution;
data solr1;
set solr;
/*
Alpha=&alpha;
t=tinv(1-&alpha/2,DF);
LowerCL=Estimate-t*StdErrPred;
UpperCL=Estimate+t*StdErrPred;
*/
CLpm=(Upper-Lower)/2;
drop StdErrPred tValue Probt;
format Estimate Lower Upper CLpm 5.&deceff DF 5.0;
if effect="Intercept" or effect="StrokeSet" or effect="&predboat";

proc sort;
by Effect Gender BoatClass Estimate;
/*
title2 "Random-effect solution (&unitsrawlog)";
title3 "Intercept is boat indiv differences in mean efficiency";
*title4 "Warning: after adjusting for between-boat differences in mean &predboat";
proc print data=solr1 noobs;
var Effect Gender BoatClass BoatID Estimate     DF     Alpha  Lower  Upper
        CLpm;
where effect="Intercept";
by Effect Gender BoatClass;
run;
*/
data predboat;
set solr1;
if effect="&predboat";
*drop StrokeSet;

title2 "Random-effect solution (&unitsrawlog)";
title3 "&predboat is relative difference from mean slope";
proc print data=predboat noobs;
var Effect Gender BoatClass BoatID Estimate     DF     Alpha  Lower  Upper
        CLpm;
```

```
by Effect Gender BoatClass;
run;

/*
data date;
set solr1;
if effect="Date";
drop BoatID StrokeSet;

title2 "Random-effect solution (&unitsrawlog)";
title3 "Date is mean differences between dates, e.g., due to changes in environment";
proc print data=date noobs;
var Effect Gender BoatClass Date     Estimate        DF      Alpha  Lower  Upper
        CLpm;
by Effect Gender BoatClass;
run;
*/
/*
data strokeset;
set solr1;
if effect="StrokeSet" and estimate ne 0; *with subjec=BoatID we get lots of zeros;
drop BoatID Date;

proc sort;
by Gender BoatClass StrokeSet;

proc sort data=decodeset;
by Gender BoatClass StrokeSet;

*proc print data=strokeset;run;

data strokeset1;
merge decodeset strokeset;
by Gender BoatClass StrokeSet;

title2 "Random-effect solution (&unitsrawlog)";
title3 "StrokeSet is boat mean differences between races within dates, e.g., due to
changes in environment";
proc print noobs;
var Gender Boatclass StrokeSet BoatID date raceTime Estimate Lower Upper CLpm
Alpha;
format Estimate Lower Upper CLpm 5.&deceff;
by Gender BoatClass;
run;
*/

/*
data strokeside;
set solr1;
if effect="Participant*Side";
```

```
drop StrokeSet;

*proc print data=decodeside;run;

data strokeside1;
merge decodeside strokeside;
by Gender BoatClass Participant Side;

proc sort;
by Gender BoatClass BoatID Side;

title3 "Participant and StrokeSide are consistent efficiency across strokes and stroke
sets";
title4 "(additional to the fixed effect of Side)";
proc print noobs;
var Gender Boatclass BoatID Side Participant Estimate Lower Upper CLpm Alpha;
by Gender Boatclass;
format Estimate Lower Upper CLpm 5.&deceff;
by Gender BoatClass;
run;
*/

*proc print data=cov;run;

/*
data lsm1;
set lsm;
array a estimate lower upper;
do over a;
  *a=100*exp(a/100)-100; *for modeling of change scores;
  if &logflag=1 then a=exp(a/100);
  end;
CLpm=(upper-lower)/2;
drop Effect Stderr tValue Probt;

title2 "Least-squares means";
options ls=80 ps=82;
proc print data=lsm1 noobs;
*var Gender Boatclass estimate lower upper CLpm DF;
format estimate lower upper CLpm 5.&decdep;
by Gender Boatclass;
run;
options ps=52;

data lsmdiff1;
set lsmdiff;
array a estimate lower upper;
if &logflag=1 then do over a;
  a=100*exp(a/100)-100;
  end;
```

```
CLpm=(upper-lower)/2;
drop stderr tValue probt;

options ps=80;
title2 "Least-squares mean differences (&unitsrawlog)";
proc print data=lsmdiff1 noobs;
var Race _Race Side _Side estimate CLpm lower upper alpha;
format estimate CLpm lower upper 5.&deceff DF 5.0; *Probt best5.;
*where &logflag=0;
by Gender Boatclass;
*where Effect="Device" or Effect="SerialNumber(Device)" and Device=_Device;
run;

*title2 "MBI for least-square mean diffs with a given smallest important for means of
&magnithresh (&unitsrawlog)";
title2 "MBI for the above with a given smallest important for means of &magnithresh
(&unitsrawlog)";
data lsmdiff1;
*set lsmdiff;
set lsmdiff;
*if index("&dep","Ratio") or "&dep"="TrainPerfPercent"; *measures where lsmeans
are differences from coach prescription;
length Prob $ 8 Magni $ 4;
MagniThresh=&MagniThresh;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh))/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh))/StdErr,DF);
if &LogFlag=1 then do;
  if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  else do;
    ChancePos=100*(1-ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  end;
ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
ClinFlag=1; *want all inferences to be clinical initially;
*if index(label,"2SD") then ClinFlag=0; *covariates definitely need to be non-clinical;

*clinical inferences;
if clinflag then do;
ChPos=ChancePos; ChNeg=ChanceNeg;
if MagniThresh<0 then do;
  ChPos=ChanceNeg; ChNeg=ChancePos;
  end;
Prob=""; Magni=""; Precision="unclear";
if ChNeg<0.5 then do;
```

```
  Precision="@25/.5%";
  if ChNeg<0.1 then Precision="@5/.1% ";
  if ChanceTriv>25 then Magni="triv";
  if ChPos>25 then Magni="bene";
  Prob="possibly";
  if ChPos>75 or ChanceTriv>75 then Prob="likely  ";
  if ChPos>95 or ChanceTriv>95 then Prob="v.likely";
  if ChPos>99.5 or ChanceTriv>99.5 then Prob="m.likely";
  end;
else do; *i.e., ChNeg>0.5;
  if ChPos<25 then do;
    Precision="@25/.5%";
    if ChPos<5 then Precision="@5/.1% ";
    if ChanceTriv>25 then Magni="triv";
    if ChNeg>25 then Magni="harm";
    Prob="possibly";
    if ChNeg>75 or ChanceTriv>75 then Prob="likely  ";
    if ChNeg>95 or ChanceTriv>95 then Prob="v.likely";
    if ChNeg>99.5 or ChanceTriv>99.5 then Prob="m.likely";
    end;
  end;
if Precision="unclear" and
  (MagniThresh>0 and ORPosNeg>25/75/(0.5/99.5) or MagniThresh<0 and
ORNegPos>25/75/(0.5/99.5))
  then do;
  Precision="OR>66.3";
  Magni="bene";
  if ChPos>25 then Prob="possibly";
  if ChPos>75 then Prob="likely  ";
  if ChPos>95 then Prob="v.likely";
  if ChPos>99.5 then Prob="m.likely";
  end;
output;
end;

*mechanistic inferences;
ClinFlag=0;
Precision="unclear";
Prob="";
Magni="";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then Precision="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then Precision="@99%  ";
if Precision ne "unclear" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
```

```
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
if Precision ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
*end;
output;

data lsmdiff2;
Units="Raw";
if &logflag then Units="%";
set lsmdiff1;
if estimate=0 then do;
  estimate=.; magnithresh=.; magni=""; Precision=""; Prob=""; Units="";
  end;
array a estimate lower upper;
if &logflag then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(Upper-lower)/2;
rename df=DegFree;
run;

*options ls=135 ps=80;
title3 "Non-clinical inferences";
title4 "Magnithresh is the given smallest important difference for means";
title5 "Units for estimates, confidence limits and smallest important are &unitsrawlog";
proc print data=lsmdiff2 noobs;
where clinflag=0;
var Race Side _Race _Side Units estimate CLpm lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos Prob Magni Precision;
format  DeviceMean ViconMean estimate CLpm lower upper MagniThresh 5.&deceff
Probt best5. ChanceNeg ChanceTriv
  ChancePos 5.1 DegFree 5.0;
by Gender Boatclass;
*where clinflag=0 and (Effect="Device" or Effect="SerialNumber(Device)" and
Device=_Device);
run;
*/
/*
*lsmestimates;
data lsmest1;
set lsmest;
array a estimate lower upper;
if &logflag=1 then do over a;
  a=100*exp(a/100)-100;
  end;
```

```
CLpm=(upper-lower)/2;
if estimate=0 then do; estimate=.; DF=.; end;
drop stderr tValue probt;

options ps=80;
title2 "Least-squares mean estimates (&unitsrawlog)";
proc print data=lsmest1 noobs;
var Position SRgroup Label Estimate--CLpm;
format estimate CLpm lower upper 5.&deceff DF 5.0 Probt best5.;
*where &logflag=0;
*by Gender Boatclass;
*where Effect="Device" or Effect="SerialNumber(Device)" and Device=_Device;
run;

title2 "MBI for least-square mean estimates with a given smallest important for means
of &magnithresh (&unitsrawlog)";
data lsmest1;
set lsmest;
*if index("&dep","Ratio") or "&dep"="TrainPerfPercent"; *measures where lsmeans
are differences from coach prescription;
length Prob $ 8 Magni $ 4;
MagniThresh=&MagniThresh;
ChancePos=100*(1-ProbT(-(estimate-abs(MagniThresh))/StdErr,DF));
ChanceNeg=100*ProbT(-(estimate+abs(MagniThresh))/StdErr,DF);
if &LogFlag=1 then do;
  if Magnithresh>0 then do;
    ChancePos=100*(1-ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  else do;
    ChancePos=100*(1-ProbT(-(estimate+100*log(1+MagniThresh/100))/StdErr,DF));
    ChanceNeg=100*ProbT(-(estimate-100*log(1+MagniThresh/100))/StdErr,DF);
    end;
  end;
ChanceTriv=100-ChancePos-ChanceNeg;
ORPosNeg=ChancePos/(100-ChancePos)/(ChanceNeg/(100-ChanceNeg));
ORNegPos=1/ORPosNeg;
ClinFlag=1; *want all inferences to be clinical initially;
*if index(label,"2SD") then ClinFlag=0; *covariates definitely need to be non-clinical;

*clinical inferences;
if clinflag then do;
ChPos=ChancePos; ChNeg=ChanceNeg;
if MagniThresh<0 then do;
  ChPos=ChanceNeg; ChNeg=ChancePos;
  end;
Prob=""; Magni=""; Precision="unclear";
if ChNeg<0.5 then do;
  Precision="@25/.5%";
  if ChNeg<0.1 then Precision="@5/.1% ";
```

```
  if ChanceTriv>25 then Magni="triv";
  if ChPos>25 then Magni="bene";
  Prob="possibly";
  if ChPos>75 or ChanceTriv>75 then Prob="likely  ";
  if ChPos>95 or ChanceTriv>95 then Prob="v.likely";
  if ChPos>99.5 or ChanceTriv>99.5 then Prob="m.likely";
  end;
else do; *i.e., ChNeg>0.5;
  if ChPos<25 then do;
    Precision="@25/.5%";
    if ChPos<5 then Precision="@5/.1% ";
    if ChanceTriv>25 then Magni="triv";
    if ChNeg>25 then Magni="harm";
    Prob="possibly";
    if ChNeg>75 or ChanceTriv>75 then Prob="likely  ";
    if ChNeg>95 or ChanceTriv>95 then Prob="v.likely";
    if ChNeg>99.5 or ChanceTriv>99.5 then Prob="m.likely";
    end;
  end;
if Precision="unclear" and
  (MagniThresh>0 and ORPosNeg>25/75/(0.5/99.5) or MagniThresh<0 and
ORNegPos>25/75/(0.5/99.5))
  then do;
  Precision="OR>66.3";
  Magni="bene";
  if ChPos>25 then Prob="possibly";
  if ChPos>75 then Prob="likely  ";
  if ChPos>95 then Prob="v.likely";
  if ChPos>99.5 then Prob="m.likely";
  end;
output;
end;

*mechanistic inferences;
ClinFlag=0;
Precision="unclear";
Prob="";
Magni="";
ORPosNeg=.; ORNegPos=.;
if ChanceNeg<5 or ChancePos<5 then Precision="@90%  ";
if ChanceNeg<0.5 or ChancePos<0.5 then Precision="@99%  ";
if Precision ne "unclear" then do;
  Magni="+ive ";
  if estimate<0 then Magni="-ive ";
  if ChancePos>5 or ChanceNeg>5 then Prob="unlikely";
  if ChancePos>25 or ChanceNeg>25 then Prob="possibly";
  if ChancePos>75 or ChanceNeg>75 then Prob="likely  ";
  if ChancePos>95 or ChanceNeg>95 then Prob="v.likely";
  if ChancePos>99.5 or ChanceNeg>99.5 then Prob="m.likely";
  end;
```

```
if Precision ne "unclear" and ChanceTriv>75 then do;
  Magni="triv.";
  Prob="likely  ";
  if ChanceTriv>95 then Prob="v.likely";
  if ChanceTriv>99.5 then Prob="m.likely";
  end;
*end;
output;

data lsmest2;
Units="Raw";
if &logflag then Units="%";
set lsmest1;
if estimate=0 then do;
  estimate=.; magnithresh=.; magni=""; Precision=""; Prob=""; Units="";
  end;
array a estimate lower upper;
if &logflag then do over a;
  a=100*exp(a/100)-100;
  end;
CLpm=(Upper-lower)/2;
rename df=DegFree;
run;

*options ls=135 ps=80;
title3 "Non-clinical inferences";
title4 "Magnithresh is the given smallest important difference for means";
title5 "Units for estimates, confidence limits and smallest important are &unitsrawlog";
proc print data=lsmest2 noobs;
where clinflag=0;
var Position SRgroup Label Units estimate CLpm lower upper alpha DegFree
  MagniThresh ChanceNeg ChanceTriv ChancePos Prob Magni Precision;
format estimate CLpm lower upper MagniThresh 5.&deceff Probt best5. ChanceNeg
ChanceTriv
  ChancePos 5.1 DegFree 5.0;
*by Gender Boatclass;
*where clinflag=0 and (Effect="Device" or Effect="SerialNumber(Device)" and
Device=_Device);
run;
*/
%mend;

%let alpha=0.1;
%let decdep=1;
%let deceff=1;
%let nob=;
%let convcrit=CONVH=1E-8 convf=1E-8;
%let StdzedMagniThresh=0.20; *smallest stdized beneficial change;
%let MagniThresh=0.3; *smallest beneficial change;
%let parms=;
```

```
*let title1=;
%let subset=if StrokeNo>10;

%let dep=AvBoatVel;
%let logflag=1;
%let predadjust=StrokeRate;
%let decpredadjust=1;
%let predadjust=PowerPeach;
%let decpredadjust=0;

%let nob=;
%let parms=;
%let type=type=un;
%let tvalue=4.5;

%let predboat=PhaseLength;
%let phase=1;
%let logflagpred=0;
%let decpredboat=3;
%anaboat;

%let phase=2;
%anaboat;
%let phase=3;
%anaboat;
%let phase=4;
%anaboat;
%let phase=5;
%anaboat;
%let phase=6;
%anaboat;

*if Phase=3 and PhaseLength>1.25;
*if Phase=4 and PhaseLength>0.8;

%let predboat=Jerk;
%let decpredboat=1;
%let phase=1;
%anaboat;
%let phase=2;
%anaboat;
%let phase=3;
%anaboat;
%let phase=4;
%anaboat;
%let phase=5;
%anaboat;
%let phase=6;
%anaboat;
```

```
%let predboat=Jerk;
%let decpredboat=1;
%let phase=1;
%anaboat;
%let phase=2;
%anaboat;
%let phase=3;
%anaboat;
%let phase=4;
%anaboat;
%let phase=5;
%anaboat;
%let phase=6;
%anaboat;

%let predboat=Filtered;
%let decpredboat=2;
%let phase=1;
%anaboat;
%let phase=2;
%anaboat;
%let phase=3;
%anaboat;
%let phase=4;
%anaboat;
%let phase=5;
%anaboat;
%let phase=6;
%anaboat;

%let predboat=TimeAboveZero;
%let decpredboat=2;
%anaboat;

%let predboat=TimeBelowZero;
%let decpredboat=2;
%anaboat;

%let predboat=AreaUnderCurve;
%let decpredboat=2;
%anaboat;


%let predboat=Phase23;
%let phase=23;
%let decpredboat=2;
%anaboat;

%let predboat=Phase34;
%let phase=34;
```

```
%let decpredboat=2;
%anaboat;

%let predboat=Phase61;
%let phase=61;
%let decpredboat=2;
%anaboat;

%let predboat=Phase56;
%let phase=56;
%let decpredboat=2;
%anaboat;
```