Acceleration and Fatigue in Soccer

by

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DOCTORATE OF PHILOSOPHY

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ABSTRACT

This thesis investigated acceleration in soccer and the ability to improve acceleration capacity using supplementation and a training intervention both separately and in combination. Study one determined the validity and reliability of 5 and 10 Hz global positioning systems (GPS) for measuring instantaneous speed during the acceleration, deceleration and constant speed phase of straight-line running. The criterion measure used to assess GPS validity was instantaneous speed recorded using a tripod-mounted laser. Ten Hz GPS devices were 2-3 times more accurate than 5 Hz when compared to a criterion value for instantaneous speed during tasks completed at a range of speeds (coefficient of variation; 3.1 - 11.3%). Similarly, 10 Hz GPS were up to 6-fold more reliable for measuring instantaneous speed than 5 Hz units (coefficient of variation; 1.9 - 6%). Newer GPS may provide an acceptable tool for the measurement of constant speed, acceleration and deceleration during straight-line running and have sufficient sensitivity for detecting changes in performance in team sport. However, researchers must account for the inherent match-to-match variation reported using these devices.

Study two quantified the acceleration and high-speed running of elite Australian soccer players. Player movements were observed from 29 players during domestic Australian competition using GPS. Effort occurrence were determined for high-speed running, sprinting and maximal accelerations. The commencement and final speed of maximal accelerations were also identified. Players undertook an 8~fold greater number of maximal accelerations than sprints per game (65 ± 21 vs. 8 ± 5). Of maximal accelerations ~98% commenced from a starting speed lower than what would be considered high-speed running while ~85% did not cross the high-speed running threshold. Maximal accelerations are frequently undertaken during a match often occurring at low speeds. Excluding maximal accelerations in match analysis research may underestimate the amount of high-intensity movements undertaken.

Study three determined whether sodium bicarbonate ($NaHCO_3$) ingestion prior to repeat sprint exercise (RSE) enhanced acceleration and/or lowered venous plasma potassium concentration ($[K^+]_{pl}$) during RSE and recovery. This study also assessed the effect of chronic $NaHCO_3$

ingestion prior to training sessions during 4 weeks of repeat sprint training (RST) compared to placebo ingestion, on acceleration and K^+ regulation. Fourteen healthy adults were randomly placed into an experimental (EXP, $NaHCO_3$ ingestion before RSE) or a placebo (CON, placebo ingestion before RSE) group. A pre-training session of RSE (3 sets of five, 4 s sprints on a non-motorised treadmill with 20 s of passive recovery between sprints and 4.5 minutes of passive rest) was completed in which both groups ingested the placebo before exercise. The EXP group completed a second pre-training RSE session where they ingested $NaHCO_3$ before RSE. The EXP and CON groups then completed twelve RST sessions ingesting either $NaHCO_3$ or placebo, respectively, before each training session. Both groups then completed a post-training RSE session in which they ingested the placebo before RSE. In the EXP group all RSE performance measures (acceleration, peak and mean speed and mean power) were not improved and there was no difference in $[K^+]_{pl}$ (P=0.957) after the ingestion of $NaHCO_3$ when compared to placebo prior to the four weeks of RST. Following four weeks of RST the CON group had small improvements across all sets in acceleration (6.6 – 7.7%, ES; 0.32 – 0.37) peak and mean speed (4.0 – 6.3%, ES; 0.33 – 0.51 and 3.8 – 5.8, ES; 0.31 – 0.47, respectively) and mean power (4.5– 8.8%, ES: 0.21 – 0.40). The EXP group only had small improvements in acceleration in set 1 and 2 (4.8 – 5.4%, ES; 0.20 – 0.22) and peak and mean speed in set 2 (3.6%, ES; 0.24 and 3.8%, ES; 0.25). Both groups had an increase in $[K^+]_{pl}$ after training (P=0.006) however there was no difference between groups (P=0.647). The acute ingestion of $NaHCO_3$ does not improve acceleration performance or lower $[K^+]_{pl}$ during or after RSE. Four weeks of RST can result in small improvements in acceleration, however, these improvements are not enhanced with the addition of $NaHCO_3$ ingestion. Therefore, whilst RST is recommended as a training tool to improve acceleration, the concomitant ingestion of $NaHCO_3$ is unnecessary.

The findings of this thesis identify that soccer players frequently accelerate at a maximal rate during competition. Therefore the ability to improve acceleration performance is desirable to soccer players/coaches. Acceleration can be improved with RST, however, the addition of $NaHCO_3$ ingestion does not further enhance performance.

STUDENT DECLARATION

"I, Matthew C. Varley, declare that the PhD thesis entitled "Acceleration and Fatigue in Soccer" is no more than 100,000 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".

Signature Date

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ABBREVIATIONS

GENERAL

[ion]	ion concentration
$\Delta[K^+]$	change in $[K^+]$
3-*O*-MFPase	3-O-Methyl fluorescein phosphatase
ANOVA	analysis of variance
ADP	adenosine 5’ diphosphate
ATP	adenosine 5’ triphosphate
Ca^{2+}	calcium ion
$CaCO_3$	calcium carbonate
CBT	computer based tracking system
CI	confidence intervals
Cl^-	chloride anion
CO_2	carbon dioxide molecule
CV	coefficient of variation
dm	dry muscle
$dm.s^{-1}$	dry muscle per second
DIV	division
e	extracellular
E_m	muscle membrane potential
ES	effect size
FI	fatigue index
g	grams
GPS	global positioning system
H^+	hydrogen ion
H_2O	water molecule
HCO_3^-	bicarbonate anion

HIA	high-intensity activity
HiSR	high-speed running
HDOP	horizontal dilution of position
Hz	hertz
i	intracellular
$J.kg^{-1}.min^{-1}$	joules per kilogram per minute
K^+	potassium ion
km	kilometres
$km.hr^{-1}$	kilometres per hour
Lac^-	lactate anion
LSA	low-speed acceleration
m	metres
$m.s^{-1}$	metres per second
$m.s^{-2}$	metres per second per second
min	minutes
mm	millimetres
mM	millimolar
$mmol.kg^{-1}$	millimolar per kilogram
MSS	maximal sprint speed
mV	millivolt
Na^+	sodium ion
NaCl	sodium chloride
NAD^+	nicotinamide adenine dinucleotide
$NaHCO_3$	sodium bicarbonate
Na^+,K^+-ATPase	sodium-potassium adenosine triphosphate
NMT	non-motorised treadmill
O_2	oxygen molecule
pl	plasma

P_{met}	metabolic power
r	correlation coefficient
RSA	repeat sprint ability
RSE	repeat sprint exercise
RSS	repeat sprint sequences
RST	repeat sprint training
s	seconds
SD	standard deviation
SEE	standard error of the estimate
SEM	standard error of the measurement
Semi-Auto	semi-automated tracking system
SL	stride length
SR	sarcoplasmic reticulum
SWC	smallest worthwhile change
VHiSR	very high-speed running
$\dot{V}O_2$	oxygen consumption
$\dot{V}O_{2max}$	maximum oxygen consumption
$\dot{V}O_{2peak}$	peak oxygen consumption
$v\dot{V}O_{2peak}$	speed at peak oxygen consumption
VT_2	ventilatory threshold
$W.kg^{-1}$	work per kilogram
yd	yards
yrs	years

PUBLICATIONS

The following publications are presented in support of this thesis:

Peer review publicationsarising directly from this thesis

1. **Varley, M. C.,** Fairweather, I. H. & Aughey, R. J. (2012). Validity and reliability of GPS for measuring instantaneous velocity during acceleration, deceleration and constant motion. *Journal of Sports Sciences*, 30, 121-127. (Study 1, Chapter 3)

2. **Varley, M. C.,** & Aughey, R. J. (2012). Acceleration profiles in elite Australian soccer. *International Journal of Sports Medicine (Accepted for publication 15/08/2012, DOI: 10.1055/s-0032-1316315).* (Study 2, Chapter 4)

3. **Varley, M. C.,** McKenna, M. C., Anderson, M., Stepto, N. K. & Aughey, J. R. (2012). The efficacy of sodium bicarbonate ingestion and repeat sprint training for improving acceleration capacity and K^+ regulation during repeat sprint exercise. *(Being prepared for submission to European Journal of Applied Physiology)* (Study 3, Chapter 5)

PUBLICATIONS ARISING DURING CANDIDATURE

The following peer reviewed publications arose during candidature:

1. **Varley, M. C.,** Aughey, R. J,. & Gabbett, T. J. Activity profiles of professional soccer, rugby league, and Australian football match-play. *Journal of Sports Sciences. (Under review)*

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4. **Varley, M. C.,** Elias, E. P. & Aughey, R. J. (2012). Current match-analysis techniques' underestimation of intense periods of high-speed running. *International Journal of Sports Physiology and Performance,*7, 183 – 185.

5. Levinger, I., **Varley, M. C.,** Jerums, G., Hare, D. L. & Selig, S. (2011). Oxygen kinetics during early recovery from peak exercise in patients with Type 2 diabetes. *Diabetic Medicine,* 28, 612-617.

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CHAPTER 1. INTRODUCTION

In soccer, players perform movements during competition and training which vary greatly in their energetic demand and the speed at which they are performed. Quantification of these movements can provide an activity profile of each athlete. While individual profiles can highlight an athlete's specific strengths and weaknesses, the grouping of profiles by variables, such as standard of play (e.g. elite vs. sub-elite) or positional role (midfielder vs. defender), can provide a set of normative data representative of the movements undertaken by each population. This information can help identify the movements that are commonly performed and considered important to elite performance. Specific training interventions can be designed to improve performance of these movements and physically prepare athletes for competition.

Movements that occur at high speeds, such as high-speed running and sprinting, are considered important indicators of physical performance. This is because the number of efforts and distance covered at a high speed, during competition, are greater in elite compared to sub-elite players (Mohr, Krustrup, & Bangsbo, 2003). Consequently, the majority of soccer training studies have focused on improving the performance of high-speed movements. Within a given standard of competition the more successful teams perform less high-speed running than the less successful teams (Rampinini et al., 2009a). Therefore, while still an important attribute in soccer, physical training should not be limited to improving high-speed running.

Acceleration, defined as the rate of change in speed, is an energetically demanding activity (Osgnach et al., 2010). In soccer, the capacity to rapidly accelerate can be decisive in winning key match outcomes, such as being first to the ball or creating or stopping goal scoring opportunities. Few studies have quantified acceleration performance during a soccer match. Often, match analysis only includes high-speed movements when reporting high-intensity activity. The exclusion of accelerations, which can occur at low speeds, would result in an underestimation of high-intensity activity.

The ability to improve an athlete's capacity to accelerate and to do so repeatedly would be advantageous to the athlete during competition. Interventions often used to improve physical capacity include specific training protocols and/or the supplementation of ergogenic aids. Repeat-sprint training can improve the capacity to accelerate throughout repeated efforts (Serpiello et al., 2011). However, the performance enhancing effects of sodium bicarbonate ingestion prior to exercise are equivocal. To date, no study has investigated the effects of sodium bicarbonate ingestion on acceleration performance. Further, it is unknown whether the combination of sodium bicarbonate supplementation throughout a training intervention would have a synergistic effect on performance and warrants future investigation.

This thesis will therefore investigate the reliability and validity of current match analysis technology to measure acceleration. This technology will then be used to assess the acceleration profile of elite soccer players during competition. Further, it will investigate the ability of sodium bicarbonate ingestion and repeat-sprint training independently and in combination to enhance acceleration performance.

CHAPTER 2. REVIEW OF LITERATURE

2.1 Match analysis methodologies

2.1.1 Match analysis in sport

Match analysis involves the quantification of a player's movement during a game. This information is commonly reported as the distance covered, time spent or number of efforts performed in pre-determined movement categories which in combination provide the activity profile of a player. Sport practitioners can then use this information to monitor changes in physical performance over time, quantify the physical strain imposed upon an athlete and design specific conditioning drills that replicate in-game movements. Further, it allows the activity profile of a player to be compared to a similar population, e.g. team-mates and opposition, or to a different population within the sport, e.g. standard of play, age and region.

Over the last four decades an assortment of match analysis techniques have been utilised, differing in both application and technology. The notable advancements in technology have enabled an increased efficiency in the collection of large data sets and improved both accuracy and reliability in the measurement of human locomotion. The use of different analysis systems makes comparison amongst the literature difficult to interpret. Further, all measurement tools should undergo and meet the requirements for quality control, as without valid and reliable measures, any data collected is meaningless (Safrit, 1989). However, match analysis technology is often released with little scientific evidence of the system's validity and reliability from the manufacturer (Edgecomb & Norton, 2006). Subsequently, researchers have been required to test the accuracy and reliability of these systems to measure distance and speed. Given these systems are used in a variety of sports, a range of tests are often required to assess the sport-specific ecological validity of the analysis system.

2.1.2 Validity and reliability of match analysis systems

Amongst the scientific community there are many definitions of validity, however this thesis will refer to validity as the ability of a measurement tool to reflect what it is designed to measure (Atkinson & Nevill, 1998). Therefore, validation of a match analysis system should assess the ability of the system to measure either distance or speed compared to a criterion measure. The lack of a

"gold-standard" measurement tool that can be used as a criterion measure led to an absence of system validation in early match analysis research (Reilly & Thomas, 1976). Conversely, more recent studies have utilised a range of different criterion measures when assessing newer technology, resulting in an increase in the number of validation studies (Coutts & Duffield, 2010; Di Salvo et al., 2006; Duffield et al., 2010; Jennings et al., 2010a; MacLeod et al., 2009). The statistical methods used to assess the precision of a system can also differ between studies and can include, the standard error of the estimate (SEE), the standard error of the measurement ([SEM] also referred to as the typical error of the measurement) and the correlation coefficient (*r*).

Reliability is the ability of a measurement tool to consistently provide the same measure (Baumgartner, 1989). Therefore, a measurement tool can be reliable without being valid, however, for it to be considered valid, it must be reliable (Baumgartner, 1989). As a researcher may use match analysis to monitor the changes in physical performance of an individual or compare activity profiles between populations, it is critical that the match analysis system is reliable (Drust, Atkinson, & Reilly, 2007).

The reliability of an analysis system is assessed through test-retest observations, which can be performed in several ways depending on whether an observer is required to input data during the analysis. Intra-observer reliability establishes whether the individual is consistent in their subjective determination of movements. This is assessed by measuring the observers' reproducibility of results for the same match on multiple occasions (Krustrup & Bangsbo, 2001). When multiple observers are used, inter-observer reliability is essential to identify discrepancies in the subjective interpretation of movement categories. Inter-observer reliability is determined by comparing independently measured results of the same player as recorded by two or more observers (Withers et al., 1982). If the analysis system does not require an observer, then the reliability of the system is assessed over a number of repeated trials (test-retest). However, as each trial requires the movement of an individual being tracked, within-subject error will be introduced as it is extremely difficult for a player to replicate their movements (Drust, Atkinson, & Reilly, 2007). This leads to difficulty in determining whether measurement error is from the system or the player. Different statistical methods have been used to

assess reliability in match analysis research, which include; the typical error expressed as a coefficient of variation (CV) and test re-test correlations.

The following sections will discuss the different match analysis techniques that have been used in team-sports and the validity and reliability of each system where applicable.

2.1.3 Notational analysis

Notational analysis was the earliest method of team-sport match analysis. This technique requires an observer to subjectively quantify the match activities undertaken by an individual player or the whole team (Brooke & Knowles, 1974; Reilly & Thomas, 1976), allowing a factual evaluation of match events without the bias of a coach. Originally notational analysis was conducted whereby observers on the sideline would record in-game outcomes by pen and paper while watching a match (Brooke & Knowles, 1974). Due to the relatively quick pace of the game and the need for accuracy, a coding system for describing match activities was often implemented allowing a faster recording of the data (Brooke & Knowles, 1974; Reilly & Thomas, 1976).

Although notational analysis is more commonly associated with recording tactical and technical information, such as the percentage of successful passes or goal-scoring patterns during offensive play (Garganta, Maia, & Basto, 1997), it has also been used to track player movement (Brooke & Knowles, 1974). One method required an observer to record player movement during a match by making subjective estimates of the distances travelled at pre-selected activity categories e.g. standing, walking, jogging or sprinting. A symbol was assigned to each activity and recorded in 1 min blocks, with a recording referring to 4.6 m (5 yd) of travel. These symbols were transposed post-match and the frequency, total distance and distance covered per minute calculated for each activity.

As each movement category is subjectively determined at the discretion of an observer the accuracy of notational analysis is often questionable, especially as validity is rarely reported. In the above study, inter-observer reliability was determined for total distance per minute and frequency of sprints performed with reliability coefficients of 0.61 and 0.98 respectively (Brooke & Knowles, 1974). The strong correlation for sprint frequency suggests notational analysis may be useful for collecting data on the frequency of match activities, such as tackling, heading, turning, jumping and sprinting (Reilly & Thomas, 1976; Withers, et al., 1982). However, it is limited in providing information on speed and

distance due to both the skill and speed of the analyst and the inability for the game to be re-analysed (Spencer et al., 2005). Researchers should therefore opt for more recent match analysis methodologies when quantifying the movements of team-sports athletes.

2.1.4 Manual video analysis

Manual video analysis requires matches to be filmed using either single or multiple video cameras and has been commonly used in soccer (Bangsbo, Nørregaard, & Thorsø, 1991; Drust, Reilly, & Rienzi, 1998; Mayhew & Wenger, 1985; Mohr, Krustrup, & Bangsbo, 2003; Ohashi et al., 1988; Reilly & Thomas, 1976; Withers, et al., 1982). Footage can be analysed post-match eliminating the time restrictions of notational analysis as the observer can pause, review and slow-down the film.

In team-sports, such as soccer, a camera is usually positioned at the half-way point of the pitch in an elevated position of 3-20 m and approximately 5-30 m from the sideline (Dobson & Keogh, 2007). There have generally been two types of camera placements used to film matches. The first uses either one or multiple cameras to focus on a single player for a period of time, typically either a half or the whole game (Mohr, Krustrup, & Bangsbo, 2003; Reilly & Thomas, 1976; Withers, et al., 1982). This allows the observer to zoom in on a player, while keeping a small area of the field in view. Reference points on the pitch are then used to determine movement distances and speeds. The disadvantage of this method is that a separate camera is needed for each player tracked, often resulting in a small sample size. Tracking only a single player per game does not provide an accurate portrait of the physical profiles of the sport as this can be influenced by the individual's style of play, involvement in the game and playing position (Bradley et al., 2011; Di Salvo et al., 2007; Rampinini et al., 2007b). Furthermore, there is limited opportunity for comparisons of physical performance to be made between teammates or opposing players (Drust, Atkinson, & Reilly, 2007).

The second type of placement requires two cameras, each focusing on one half of the pitch with a small overlap in the centre (Spencer et al., 2004). All players can then be filmed at once, however, the smaller view of each player makes it harder for movements to be accurately analysed. The combination of camera angle, distance from the pitch, use of a still or panning technique and the fact that players are not often perpendicular to the camera can lead to a distortion of the image when the footage is replayed (Knudson & Morrison, 2002). Therefore, camera placement is a key consideration

when using manual video analysis, although it is often restricted by the location of the match due to differences in stadia design and pitch surroundings.

Several techniques have been used to calculate the speed, distance and duration of movements when using manual video analysis. One technique required the observed player to be filmed post-match covering marked distances for each movement including; jogging, striding, sprinting, moving sideways, walking backwards and jogging backwards (Reilly & Thomas, 1976; Withers, et al., 1982). An average stride length was determined and assigned to each movement. Upon reviewing the match footage, movements were coded based on the observer's subjective estimation of the individuals stride length. The time and distance covered for each movement could then be determined (Reilly & Thomas, 1976; Withers, et al., 1982). An alternative technique required the observer to categorise movements based upon running speed calculated from the time a player took to pass reference points on the field. The frequency, distance covered and duration spent in each category were then determined (Bangsbo, Nørregaard, & Thorsø, 1991; Mohr, Krustrup, & Bangsbo, 2003; Rienzi et al., 2000).

As manual video analysis requires an observer to review and code player movements, the majority of research has reported both inter- and intra-observer reliability (Krustrup & Bangsbo, 2001; Withers, et al., 1982). Inter-observer reliability for the stride-length measurement technique had an excellent correlation co-efficient of 0.998 for the total distance covered during a match (Withers, et al., 1982). However, the determination of distances covered at higher speeds, such as striding and sprinting, produced lower correlation coefficients (0.745 and 0.815 respectively). This was reportedly due to observer disagreements on the classification of discrete work intervals. The combination of striding and sprinting, into a single category improved the correlation co-efficient to 0.95 (Withers, et al., 1982). This suggests that an observers' ability to differentiate between high-speed movements is a limitation for manual video analysis. Similarly, rapid changes in speed may also be difficult to define as inter-observer reliability has been reported to decrease during change of direction and deceleration movements (Bloomfield, Polman, & O'Donoghue, 2007).

Intra-observer reliability using the field reference point technique, has been assessed with observers analysing five matches on two occasions separated by 6 months (Krustrup & Bangsbo, 2001). The

measure of total distance covered had a CV of 1% while variations in walking, low-speed, high-speed and backwards running were 2, 5, 3 and 3%, respectively (Krustrup & Bangsbo, 2001). This suggests that the reliability of manual video analysis is less compromised when using only a single observer, as separate observers may differ in their interpretation of movement classifications.

The accuracy of manual video analysis for measuring distance and speed is questionable as validity has rarely been reported. If the determination of these measures has not been assessed against a criterion measure, it is not possible to establish the accuracy of the observer's subjective classifications. Subsequently, the interpretation of player speed and distance data using this technique should be performed with caution. Given the lack of validation research, the limited sample size and the analysis process being laborious and time consuming, manual video analysis has been largely superseded by other analysis systems.

2.1.5 Computer based tracking systems

Computer based tracking systems were developed to reduce the labour intensive coding and reliability problems associated with manual video tracking. Specific analysis software was developed to provide observers with a faster way to collect, store and code match data either in real-time or retrospectively following a match (Partridge & Franks, 1993). The availability of basic and professional software packages offers both amateur and elite clubs access to tracking software depending on their available budget.

There are several types of match analysis software available. The first borrows elements of notational and manual video analysis and combines them in an efficient manner. For example using a laptop an observer can record discrete match actions and tactical information from the sidelines, designating a single key or shortcut to a particular event reducing the time taken to enter data. Match statistics can then be produced on player contribution and performance in real-time providing immediate feedback to coaches who can use this information to make tactical decisions as the game is being played. Similar to manual video analysis, if footage is available observers can review the game at a later date allowing greater accuracy and reliability in the data analysis (Ali & Farrally, 1991). Information can be provided to the coach within a couple of hours, which can be important in situations, such as tournaments where there is a short turnaround between matches (Partridge & Franks, 1993).

Other tracking software, such as “Trakperformance”, can be used to quantify the distance and duration covered by the player in selected movement categories. This requires the observer to track a player’s movement on a schematic pitch using a drawing tablet or computer. This is performed either in real-time or retrospectively via recorded footage of the game (Edgecomb & Norton, 2006). Player movement is tracked with the aid of a drawing pen or mouse with the observer simulating the speed of movement and position on the field (Burgess, Naughton, & Norton, 2006).

The validity of Trakperformance software for accurately measuring player distances was assessed using a calibrated trundle wheel pedometer as a criterion measure (Edgecomb & Norton, 2006). Although the two measures were highly correlated (r = 0.99) there was an absolute error of 7.3% in the computer tracking measure compared to the criterion, resulting in overestimations of the true distance. Larger errors were associated with tracking smaller distances (< 200 m), however, these errors were reduced as the distance tracked increased (> 2 km). The inter- and intra-observer reliability reported as the technical error of measurement was ~5.3% and ~4.7% respectively. Although Trakperformance was suggested to be an appropriate measure of player distance (Edgecomb & Norton, 2006) the software was not validated to measure player speed, an important consideration as speed is used to assign movements into different categories.

2.1.6 Semi-automated tracking systems

The development of semi-automated tracking systems in the early 2000’s was a boon for sports scientists and researchers as it allowed the tracking of multiple players simultaneously, substantially increasing the sample size and the amount of data collected. The most popular commercially available semi-automated tracking systems currently used in professional soccer are Prozone® and Amisco Pro® (Carling et al., 2008). These systems allow the simultaneous tracking of an entire team through multiple cameras placed at fixed locations around the pitch (Rampinini, et al., 2007b). Cameras are installed at optimally calculated locations with position, orientation, zoom and field of vision, based on pitch dimension and stadium structure. This allows the entire surface of play to be recorded ensuring every player can be seen for the total match duration (Carling, et al., 2008). Footage from each camera is simultaneously relayed to a high specification server and converted to high quality video files using the software PZ Stadium Manager (Di Salvo, et al., 2006). Pitch dimensions are then

determined and calibrated to allow a 2-dimensional model to be constructed and calculations made on player position. Player trajectory is sampled at 10 Hertz (Hz) and restricted to an x and y co-ordinate measured in meters from the centre circle on the pitch. Pythagoras' theorem is then used to calculate the distance covered every sample and subsequently the average speed over 0.5 s (Di Salvo et al., 2009). To ensure quality control an observer reviews this data, identifying each player and verifying the determined trajectories for that player remain constant throughout the match (Di Salvo, et al., 2006).

The validation of Prozone® for measuring displacement speeds has been assessed on several occasions (Di Salvo, et al., 2006; Di Salvo, et al., 2009). Average speed as recorded by Prozone® was compared to average speed calculated by the time it took players to pass through a set of timing gates. Several movements were performed including 60 m paced runs, 15 m maximal sprints and 20 m maximal sprints with a 90 degree turn (10 m left or right). All movements displayed a high correlation coefficient of > 0.95) and low typical error expressed as a coefficient of variation (< 1.3%) (Di Salvo, et al., 2006). Further analysis showed a mean difference in the average speed between the two methods of -0.015 s (95% confidence limits of -0.59 to 0.29). This difference was not statistically significant and was independent of running mode (linear and non-linear) and running speed (7.5 – 25.2 $km.hr^{-1}$). When pooled, all movement data showed an overall CV of 0.4% and Prozone® was concluded to be a highly accurate system for recording displacement speed (Di Salvo, et al., 2009).

The accuracy of Prozone® for determining speed may still be limited however, as the aforementioned studies only assessed average speed. Soccer players perform over 1100 movements in a given match (Bangsbo, Nørregaard, & Thorsø, 1991), of which a large number require rapid changes in speed. Therefore, instantaneous speed would be a more appropriate measure of assessment as determining distance from average speed could lead to both over- and under-estimations of the true distance covered.

Semi-automated tracking systems still require manual verification from an observer to ensure players are correctly identified and tracked. An observer is specifically required to identify players when they are occluded from the camera view, for example during player congestion at corners and free kicks, and/or during adverse environmental conditions, such as snow, heavy rain and bright light (Carling, et

al., 2008). The amount of player occlusion per game, ranges from 38 – 97% with a match average of 58% (Di Salvo, et al., 2009). Tracking accuracy then becomes dependent upon the training and experience of the observer (Barris & Button, 2008).

Inter- and intra-observer reliability for Prozone® was determined where two observers each analysed two players on two occasions 7 days apart. Both inter- and intra-observer reliability for determining the time spent in a range of movement categories produced a coefficient of variation of < 3.6%. Similar values were reported for distance covered, although these values increased for both inter- and intra-reliability during the higher speed movements with the greatest coefficient of variation being between-observer measures of time spent sprinting (6.5%) (Di Salvo, et al., 2009).

Semi-automated tracking systems have been used over entire seasons to track player movement, allowing sample sizes of over 500 players and 7000 individual match files (Bradley, et al., 2011; Bradley et al., 2009b; Di Salvo, et al., 2007; Di Salvo, et al., 2009; Gregson et al., 2010; Rampinini, et al., 2007b; Rampinini, et al., 2009a). This allows an in-depth analysis of player movements including seasonal variation, match-to-match and player-to-player variability and differences amongst playing positions, team-mates and opposition (Gregson, et al., 2010; Rampinini, et al., 2007b; Rampinini, et al., 2009a). This is a large increase in the number of subjects compared to many previous studies using older methodologies (Burgess, Naughton, & Norton, 2006; Castagna, D'Ottavio, & Abt, 2003; Mayhew & Wenger, 1985; Mohr, Krustrup, & Bangsbo, 2003; Reilly & Thomas, 1976; Strøyer, Hansen, & Klausen, 2004; Withers, et al., 1982).

Although semi-automated video tracking is currently a popular technique, it is not without its limitations. As an observer is still required, data analysis is a time consuming process, often with a 24 – 48 hour turnaround (Carling, et al., 2008). This limits the practical use of match data by a coach or sport scientist for optimising recovery and subsequent training sessions. While this is not a problem for research purposes it is a deterrent when used to provide feedback to coaches. The specific location and setup of cameras means the system is non-portable, limiting analysis to games that are played at suitably equipped stadiums (Carling, Williams, & Reilly, 2005). Often the elite clubs that use this system train at separate grounds to where they play leaving them unable to use these systems to track training sessions. Finally, the installation and continued use of semi-automated tracking systems are

expensive and often incur a monthly service charge for the analysis of match data. Therefore this system is predominantly used by clubs in the top professional soccer divisions and is not accessible to moderate or amateur level teams.

2.1.7 Issues with match analysis

Comparison of match demands between studies using different analysis techniques is inherently problematic. Subjective analysis during notational and manual video analysis is limited by the observer's ability to categorise high-speed movements as they are of short duration (Bradley, et al., 2009b; Mohr, Krustrup, & Bangsbo, 2003; Withers, et al., 1982). Evidence of this includes the overestimation of the percentage time and distance a player sprints with manual video analysis versus automatic video tracking of the same game (Roberts, Trewartha, & Stokes, 2006). This error is likely due to the observer categorising a sprint as when the player begins to accelerate as opposed to when they obtain sprinting speed. Further, when comparing manual video analysis data from the Italian Serie A to automatic video tracking from the English Premier League, distances covered at lower speeds were similar between the two leagues, yet large discrepancies existed at higher speeds. Sprinting was classified at a 16% higher speed threshold when manual video analysis was used (Mohr, Krustrup, & Bangsbo, 2003), yet total sprinting distance was 61% greater compared to automatic video tracking (Di Salvo, et al., 2009). This difference is too large to be explained by regional differences between the leagues, and is more realistically due to the differences in analysis techniques.

The direct comparison of manual video analysis, automatic video analysis and both 1 and 5 Hz global positioning system (GPS) to quantify the movement demands during a soccer match has recently been investigated (Randers et al., 2010). While distance data was not compared to a criterion measure, the various techniques revealed differences in the determination of the absolute distances covered at a range of speeds. Specifically the distance covered at a high running speed (> 3.61 m.s^{-1}) was 0.6 – 1 km greater in the automatic tracking system compared to the other techniques. Furthermore there were large between-system differences in total distance covered for all techniques. It was concluded that due to these differences when comparing results obtained by different match analysis systems some caution should be taken by the researcher.

2.2 The global positioning system

2.2.1 Background

The global positioning system is a navigational system originally developed for military use in 1973 (Lachow, 1995). The GPS operates through the use of 24 satellites that orbit the earth (Townshend, Worringham, & Stewart, 2008). Each satellite is equipped with an atomic clock and transmits low-power radio signals containing information on the exact time to a ground-based GPS receiver (Larsson, 2003). Once received, the length of time taken for the signal to travel from the satellite to the receiver is calculated by comparing the time of signal transmission to the time of arrival. The distance of the satellite from the GPS (termed pseudorange) can then be calculated by multiplying the signal travel time by the speed of light, the speed at which the signal travels (Larsson, 2003). If a minimum of four satellites are in communication with the GPS the accurate position of the receiver can be trigonometrically determined (Larsson, 2003). The global positioning system can also calculate the speed of displacement (speed) using a complex algorithm that measures the rate of change in the satellites' signal frequency (Doppler shift) caused by the movement of the receiver (Schutz & Chambaz, 1997).

In 1983, GPS technology was released for civilian use when a civilian airplane was accidentally shot down by Soviet jet interceptors after becoming lost over Soviet airspace (Enge & Misra, 1999). It was believed that access to a better navigational system may have prevented this disaster. Initially, the US Department of Defence applied an intentional degradation to the civilian satellite transmission known as Selective Availability, to limit hostile forces using the system (Schutz & Chambaz, 1997). To reduce the errors associated with Selective Availability the differential GPS was developed, which used a stationary receiver in addition to the roving GPS receiver. By placing the stationary receiver at a known and calculated position the fixed location of the differential GPS was compared with that given by the satellite, thus establishing the error in the signal. This correctional information was then sent to the roving receiver substantially reducing any errors present (Townshend, Worringham, & Stewart, 2008). The use of differential GPS as a viable method of athlete tracking was limited as units were sizeably bulkier than non-differential GPS units and weighed approximately 4 kg (Terrier et al., 2000).

In May 2000, Selective Availability was switched off thereby increasing the accuracy of non-differential GPS. As non-differential GPS are cheaper, lighter, smaller and involve a less complex data collection procedure then differential GPS they present a new opportunity in the analysis of player performance in the sporting world (Townshend, Worringham, & Stewart, 2008).

2.2.2 GPS as a player tracking tool

The first commercially available GPS designed as a tracking tool for team-sport became available in 2003 (Edgecomb & Norton, 2006). Since then the use of GPS in sport has increased substantially and it is now commonly used in team-sports, such as soccer, Australian football, rugby league and hockey (Aughey, 2010; Buchheit et al., 2010c; Gabbett, Jenkins, & Abernethy, 2012; Macutkiewicz & Sunderland, 2011). The two main manufacturers of GPS designed for player tracking are GPSports and Catapult Innovations, whose latest models are the SPI X and MinimaxV4 respectively. The typical GPS unit is approximately the size of a small mobile phone, for example the MinimaxV4 is 19 x 50 x 88 mm and weighs 67 g. Players wear the GPS unit positioned on the upper back, between the shoulder blades, in a custom-made vest. The units record distance and speed data of the player during a match that is later analysed to provide an activity profile. These devices have a battery life of up to 6 hours and can store between 4 – 60 hours of data depending on the model. If enough units are available to the researcher, an entire team can be monitored at once. Furthermore, data can be analysed in a timely manner in comparison with other techniques as an observer is not required. Information from the GPS receiver is downloaded to a computer post-match or training and can then be analysed using either commercially available or custom-built software.

Although relatively expensive, GPS are a cheaper alternative to semi-automated tracking systems without any ongoing costs, aside from service fees which may be included in the warranty. Another advantage is that GPS are a portable system allowing them to be used during training as well as home and away matches. For this reason, GPS technology is now common in countries lacking semi-automated tracking systems (Aughey, 2010, 2011b; Cunniffe et al., 2009; Duffield, Coutts, & Quinn, 2009; Farrow, Pyne, & Gabbett, 2008; Wisbey et al., 2010). However, during official soccer matches regulations restrict players from wearing anything other than their standard uniform (Di Salvo, et al., 2006). This has limited the majority of GPS research, conducted in elite soccer to youth competitions,

non-competitive matches and training sessions (Castagna et al., 2010; Tan, Dawson, & Peeling, 2012) or to competitive matches in countries where the national sporting organisation has allowed GPS data to be collected for brief periods (Duffield et al., 2011).

The use of GPS technology to quantify the physical performance of team-sports athletes is now commonplace during training and match-play (Aughey, 2010, 2011b; Brewer et al., 2010; Duffield, Coutts, & Quinn, 2009; Farrow, Pyne, & Gabbett, 2008; Wisbey, et al., 2010). Of considerable note however, is the lack of any in-house validation or reliability research made available to the consumer (Edgecomb & Norton, 2006). As the accuracy of any measurement system is critical in the application of its information, researchers have been required to perform their own validity and reliability assessments (Coutts & Duffield, 2010; Duffield, et al., 2010; Jennings, et al., 2010a; Jennings et al., 2010b). Further, the release of newer models boasting improved accuracy and reliability over their predecessors has led to a need for continual assessment. The following sections will summarise the literature in this area.

2.2.3 Sampling rate of GPS, applications to team sports

There have been two primary areas of technological advancement throughout the development of GPS being the sample rate and internal chipsets. Originally, GPS operated with a sample rate (the speed at which the GPS receives satellite signals) of 1 Hz or one sample per second. Since its inception GPS is now available at a range of sampling frequencies (5, 10 and 15 Hz). Logically, an increased sample rate should improve the precision of the unit to measure short, rapid movements, such as sprint, acceleration and deceleration efforts as these efforts are often of minimal duration (Bangsbo, Nørregaard, & Thorsø, 1991; Mohr, Krustrup, & Bangsbo, 2003). However, manufacturers of the 15 Hz technology have failed to release specific information about the collection of data and it is thought that a lower sampling rate has been supplemented with accelerometer data (Aughey, 2011a).

Improvements in the GPS chipsets may also enhance the accuracy of the units using improved algorithms to determine positional information (Coutts & Duffield, 2010). There is evidence of improved accuracy in GPS at increased sample rates (Jennings, et al., 2010a) and with newer chipsets (Coutts & Duffield, 2010), however, it is likely a combination of the two which provide a more sensitive GPS receiver.

The application of GPS in team sport provides distance and speed information of the athlete during performance. Therefore, the validity and reliability of the units to detect these measures is essential. The majority of GPS research however, has assessed distance with only a handful of studies directly assessing speed. As match analysis using GPS defines player movement categories based on speed thresholds, the ability to accurately detect speed is as important as the ability to detect distance. As this thesis assessed the validity and reliability of GPS to detect speed, the assessment of distance will only briefly be summarised.

2.2.4 Validity and reliability of GPS for measuring distance

The comparison of the literature examining the accuracy and reliability of GPS for measuring distance is difficult due to differences in the equipment used (GPS model and criterion measure), and task performed (distance, speed and linearity). Therefore, a summary of the general findings and methods used to assess the validity of GPS for measuring distance is presented in Table 2-1.

Table 2-1 Summary of the validation studies assessing global positioning systems and their application to team-sports

Study	GPS Model	Sample Rate (Hz)	Task	Criterion Measure	Variable Assessed
Edgecomb et al, 2006	SPI-10	1	Movement around an oval (125-1386 m)	Calibrated trundle wheel	Distance
Macleod et al, 2009	SPI-Elite	1	Hockey-movement based circuit	Timing gates	Distance Mean speed
Petersen et al, 2009	SPI-10 SPI-Pro MinimaxX v2.0	1 5 5	Cricket-movement based circuit 20, 30 and 40 m linear sprints	Timing gates	Distance
Coutts et al, 2010	SPI-10 SPI-Elite	1 1	Team-sport movement based circuit	Timing gates	Distance Peak speed
Gray et al, 2010	SPI-Elite	1	Linear and non-linear 200 m courses	Theodolite	Distance
Barbero-ALSArez et al, 2010	SPI-Elite	1	Repeated sprints (7 x 30 m)	Timing gates	Peak sprint speed Fatigue index
Duffield et al, 2010	SPI-Elite MinimaxX v2.0	1 5	Court-based movement drills	VICON motion analysis system	Distance Mean speed Peak speed
Jennings et al, 2010	MinimaxX v2.0	1 and 5	Team-sport movement based circuit Linear and multidirectional courses	Timing gates	Distance
Portas et al, 2010	MinimaxX v2.5	1 and 5	Soccer-movement based circuit Linear and non-linear courses	Timing gates	Distance
Waldron et al, 2011	SPI-Pro	5	10, 20 and 30 m linear sprints Moving 10m sprints	Timing gates	Distance Mean speed
Castellano et al, 2011	MinimaxX v4.0	10	15 and 30 m linear sprints	Timing gates	Distance

The manufacturer of SPI-10, SPI-Elite and SPI-Pro is GPSports, and the manufacturer of MinimaxX v2.0, v2.5 and v4.0 is Catapult Innovation

The first attempt to validate GPS for measuring the distance of team-sports movements, required participants to move around the boundary line of an Australian football oval, while wearing 1 Hz devices (Edgecomb & Norton, 2006). Total distance was assessed by comparing GPS distance to the actual distance as measured by a calibrated trundle wheel. Although GPS distance was strongly correlated to the criterion measure (r = 0.998), there was an average error of ~5%. The reliability of the units was also determined, demonstrating a technical error of measurement of 5.5%. While a good starting point, this study did not include information on the effect of different running speeds on the measurement of distance. This is an important consideration given the intermittent nature of team-sport.

More recent GPS validation methods required participants wearing GPS to perform trials involving team-sport specific movements, such as change of direction, sprinting and changes in speed (Coutts & Duffield, 2010; Jennings, et al., 2010a; Petersen et al., 2009; Portas et al., 2010). A course through which participants move was set up with the course lengths measured using either a measuring tape, trundle wheel or in one case a theodolite (Gray et al., 2010). Timing gates were then placed at specific points throughout the course to record the time the participant takes to pass known distances. The start time was identified in the raw GPS data as the first movement above 0 $m.s^{-1}$ with the participant remaining stationary before commencing the trial (Petersen, et al., 2009). The time taken to pass through the gates was used to determine the end of the trial in the raw GPS data and GPS distance was then calculated.

The majority of research suggests that a higher GPS sample rate will provide an increased precision in the measurement of distance. Interestingly, at lower speeds the differences in the error in measurement between 1 and 5 Hz GPS were minimal, however this margin increased at higher speeds (Coutts & Duffield, 2010; Jennings, et al., 2010a). For example the SEE was 1.2% lower in 5 Hz units compared to 1 Hz when walking and jogging over 20 m, however it was 5.3% lower when sprinting (Jennings, et al., 2010a). Regardless of sampling frequency, GPS accuracy was affected by speed with substantial increases in the SEE during sprinting compared to walking and striding (SEE; 2.6 – 23.8 % vs. 0.4 - 3.8%, respectively) (Petersen, et al., 2009). The accuracy of GPS also decreased over short compared to long distances ((SEE; 23.8 – 32.4% vs. 9 – 12.9%, respectively) (Jennings, et al., 2010a).

A common finding across validation studies is of a systemic underestimation of distance by GPS (Duffield, et al., 2010; Jennings, et al., 2010a; Portas, et al., 2010; Waldron et al., 2011). Early research assessing two 1 Hz units with different chipsets (SPI-10 and SPI-Elite, GPSports), reported that although both units underestimated total distance, although the newer model had less underestimation (-4.1 vs. -2.0%, respectively) (Coutts & Duffield, 2010). It was suggested that the improved accuracy was due to the different algorithms used within the chipsets supporting the claims of the manufacturers, however, the comparison of higher frequency GPS with different chipsets requires further investigation.

The reliability of GPS for measuring distance can be influenced by a number of factors. Similar to validity, GPS reliability is reduced at higher speeds. For example the variability in distance measures increased from straight line jogging to sprinting over various distances (CV; 9.1 – 22.8 and 9.8 – 39.5%, respectively) (Jennings, et al., 2010a). It is unclear if sampling frequency affects reliability with comparable results from 1 and 5 Hz GPS during linear motion (CV; 4.4 – 4.5 and 4.6 – 5.3%, respectively). However, during rapid, short distance movements 5 Hz GPS had a reduced reliability compared to 1 Hz units (CV; 3.5 – 17.8% vs. 3.6 – 9.5%) (Duffield, et al., 2010). It was speculated that this could be related to the increased amount of data collected at the higher sampling frequency. Multidirectional movements also decreased the reliability of GPS for measuring distance (Jennings, et al., 2010a; Portas, et al., 2010), however this may be due to these movements requiring rapid changes in speed.

While researchers have focused on the validation of GPS for measuring distance, the validation of speed is of equal importance, as the classification of movement categories in are based upon the speed of the player. In comparison to distance, relatively few studies have attempted to validate GPS for measuring speed, which will now be discussed.

2.2.5 Validation of GPS for measuring speed

The first study to evaluate the ability of GPS for measuring over-ground speed following the removal of Selective Availability was in 2004 (Witte & Wilson, 2004). A cyclist wore a 1 Hz GPS unit while performing relatively constant linear and curved movement and rapid acceleration/deceleration around a running track. Speed measured by GPS was assessed against a bicycle speedometer. At

constant speed along a straight path GPS speed was within 0.2 $m.s^{-1}$ of true speed measured for 45% of recorded values, with a further 19% lying within 0.4 $m.s^{-1}$. Accuracy decreased when moving along a curved path, which resulted in an underestimation of speed, that increased at higher speeds. Similarly, GPS accuracy was reduced during rapid acceleration and decelerations. It was concluded that while GPS was suitable for the determination of constant speed and steady accelerations, it was unable to resolve rapid changes in speed, most likely due to the low sampling frequency (Witte & Wilson, 2004). This initial research suggested that 1 Hz GPS may not be sufficiently sensitive enough to provide an accurate measure of speed during team-sport movements as athletes must frequently change speed and direction throughout a match (Bangsbo, Nørregaard, & Thorsø, 1991; Withers, et al., 1982). However, due to the ergometry used in this study these findings presented little ecological validity for the use of GPS in team-sports. It was not until 5 years later that GPS speed was assessed for specific use in team sports (MacLeod, et al., 2009).

The most common method to assess the accuracy of GPS to measure speed has used timing gates as a criterion measure (Table 2-1). Similar to the assessment of distance, timing gates were set up at specific distances along a course that participants wearing GPS moved through. Speed was determined by dividing the distance between the gates by the time it takes a participant to pass through them. Often timing gates were placed only a short distance apart (10 – 20 m) and the calculated speed of the participant reported as peak speed. This method is inherently problematic as any speed determined in this manner will only represent the average speed over the length of the protocol. It is therefore unsurprising that studies assessing speed in this manner have found strong correlations between GPS speed and the average speed derived by timing gates (r = 0.99 to 1) (MacLeod, et al., 2009). As team sports athletes often undertake rapid changes in speed, the measure of instantaneous speed is more appropriate.

The only study to directly assess speed during short, rapid multidirectional movements used a VICON motion analysis system as the criterion measure (Duffield, et al., 2010) which operates at 100 Hz and has a positional identification error of 0.0008% (Elliott & Alderson, 2007). Both 1 and 5 Hz GPS underestimated mean and peak speed by 10 – 30% compared to the criterion measure, with the error increasing at higher speeds and during frequent change of direction. Similarly, studies that have

assessed the measurement of distance and speed when sprinting from a standing start compared to a flying start reported a greater precision in GPS measurement in the absence of rapid changes in speed (Jennings, et al., 2010a; Waldron, et al., 2011). This greater inaccuracy during instantaneous changes in speed may be a result of the limited sampling frequency. It is therefore conceivable that higher frequency GPS will provide a more accurate measure of these movements.

In summary, the accuracy and reliability of GPS to measure both distance and speed, decreases over short distances and at high speeds. Movements fitting this description include acceleration, deceleration and change of direction efforts, which are common in team-sports. A GPS that can accurately measure accelerations and high-speed activities would be a valuable tool in team-sports as these actions are of high importance. The assessment of GPS to measure instantaneous speed and changes in speed would provide information to allow researchers to appropriately quantify these movements. As the accuracy of GPS improves at higher sampling frequencies, the validation of both 5 and 10 Hz units are required.

2.2.5.1 The application of a laser distance measurement device for determining instantaneous speed

Laser measurement devices produce valid and reliable estimates of distance from which speed data can be derived (Harrison, Jensen, & Donoghue, 2005). The LAVEG laser diode system has been used to quantify the instantaneous speed of world-class sprinters and professional soccer players (Góralczyk et al., 2003; Turk-Noack, 1998; Turk-Noack & Schmalz, 1994). Compared to timing gates which can only determine average speed based on a limited number of samples, laser devices sample at 50 Hz or greater, allowing the collection of practically instantaneous speed data. This allows a more sensitive measure of the changes in speed during rapid actions, such as acceleration and decelerations. Therefore, the laser may be a more appropriate criterion measure for the assessment of speed than timing gates.

The validation of a tracking system to accurately measure instantaneous speed would be beneficial for both researchers and sports practitioners. The accurate quantification of the high speed movements and acceleration efforts undertaken during a soccer match would provide a more detailed assessment

of the high-intensity activity profiles of players. This information would be beneficial in understanding the physically demanding movements performed by players and can assist in developing specific training drills, to enhance the performance of these movements.

2.3 Physical performance in soccer

2.3.1 Movement classifications

The widespread use of match-analysis has led to an expansion in the number of descriptors used to quantify the movements of soccer players. Originally categories typically consisted of standing, walking, jogging, running (striding) and sprinting (Brooke & Knowles, 1974; Reilly & Thomas, 1976; Withers, et al., 1982). As improvements in analysis technology provided a greater level of detail, more focus was placed on high-speed movements with running divided into moderate (hard) and high-speed (very-hard) running (Bangsbo, Nørregaard, & Thorsø, 1991; Barros, Valquer, & M, 1999; Mohr, Krustrup, & Bangsbo, 2003). Other less common categories include walking and jogging backwards and side-to-side movement (Rienzi, et al., 2000; Withers, et al., 1982).

Movement categories can be combined into more generalised groups to simplify analyses when a large number of categories are used. These generic zones are often set at a similar speed threshold allowing movements to be directly compared across studies. The most common groups are low-intensity activity, composed of walking and jogging, and high-intensity running, which consists of any category greater than or equal to running. A third group, very-high intensity running, is comprised of categories faster than running and has been sequestered from high-intensity running to enable a more detailed description of high-speed movements (Bradley, et al., 2009b; Rampinini, et al., 2007b).

Although these groups were originally referred to as intensity zones, it has been suggested that the use of the term intensity is incorrect as it implies that the player is moving at an individualised intensity (Abt & Lovell, 2009). As movement categories are often defined based on the speed of an athlete as opposed to their energetic demand, these categories depict running speed and not the relative intensity of the movement. This has led to a change in the terminology used in match analysis literature with the term intensity being replaced by either speed or speed (Gregson, et al., 2010; Osgnach, et al., 2010). In this thesis the term high-speed running will be used, where applicable, when discussing previous studies that have used the term high-intensity running.

2.3.2 Determination of speed thresholds

The designation of player movement data into specific movement categories is based on either an absolute or relative speed threshold. A relative threshold classifies movement based on an objective variable specific to the individual athlete. Variables can include performance (e.g., maximal running speed (Buchheit et al., 2010d; Harley et al., 2010)) or be derived from physiological measures (e.g., speed at the ventilatory threshold (VT_2) (Abt & Lovell, 2009)). This permits the movement of an athlete to be analysed in reference to their individual capacity as opposed to the average capacity of a group. A relative threshold can be used to make intra-player comparisons, such as monitoring a player's progress throughout the season (Abt & Lovell, 2009) or investigating the individual response to a training intervention. This could provide a more sensitive analysis of the individual's physical performance; however further research in this area is required.

The disadvantage of using a relative threshold is that it limits the ability to make comparisons of the physical performance across different players, populations and studies. For example, if a tactical role requires a player to regularly run at a high-speed, selecting a player based on their relative high-speed running does not ensure they are the fastest player from the team. Further, the periodised training approach over a season may necessitate regular athlete testing to re-establish threshold values due to changes in their physical capabilities. For example, sub-elite soccer players can improve in 30 m sprint time from the commencement to the completion of the competitive season by up to 7 and 4%, respectively (Magal et al., 2009). Similarly, professional soccer players can improve in the Yo-Yo level 2 intermittent recovery test performance from the start to the end of pre-season by up to 42% and exhibit performance increases and decreases during the competitive season (Krustrup et al., 2006a). In-season fitness testing is often limited at elite level clubs where the workload imposed upon a player is high and a constant balance between training, competition and recovery must be managed appropriately. Therefore, relative thresholds may not be a practical choice at an elite club setting.

The use of an absolute threshold is more popular in match analysis research (Bradley, et al., 2009b; Di Salvo, et al., 2009; Rampinini, et al., 2007b). A single threshold value is determined by the researcher and applied to an entire sample. It is preferable that thresholds are based on a performance or physiological variable that is representative of the entire population. However, the majority of

research which uses absolute thresholds does so without providing an evidence-based rationale for threshold selection. Although subjective in their determination, similarities can be seen in the absolute thresholds used across the match analysis literature (Table 2-2). This allows comparisons to be made between individuals, an important component in both research and competition settings as differences can be distinguished between leagues, playing levels and positions. Sets of normative data for specific populations can then be established and used as a standard to indicate where improvements may be required for both individual players and teams.

The disadvantage of using an absolute threshold is that it does not account for the relative capacity of the individual. This shortcoming was observed in professional soccer players who differed in the speed at which they began working at a high-intensity (Abt & Lovell, 2009). The designation of an absolute threshold for high-intensity running led to a substantial under-estimation of high-intensity running distance during a match compared to distance covered when using relative threshold (Abt & Lovell, 2009). This reinforces the suggested change in terminology from high-intensity to high-speed to avoid any inferences about intensity (Abt & Lovell, 2009).

The decision to use either a relative or absolute speed threshold should be based upon the goal of the researcher or the nature of the study. For example both methods of threshold determination were used to compare the number of repeat sprint sequences (RSS) performed in a match by under-13 and under-18 youth soccer players (Buchheit, et al., 2010d). When an absolute sprint threshold (> 5.28 $m.s^{-1}$) was used the older players performed a greater number of RSS whereas when a relative threshold (> 61% of individual maximal running speed) was applied the younger players performed a greater number of RSS. If the research goal was to determine age-specific differences in the ability to repeat maximal efforts, in reference to the capacity of the individual, a relative threshold is most appropriate. However if the research goal was to determine age-specific differences in the ability to repeat efforts at a high-speed, the absolute threshold should be used.

For the purpose of this literature review the comparison of studies using absolute thresholds will be made. It should be acknowledged that this is still inherently problematic due to differences in the chosen speed thresholds and the differences in match analysis technology (See section 2.1.7). Future research should attempt to identify specific absolute thresholds or ranges of acceptable speeds for

different groups of athletes as age, gender, position and standard of play have exhibited significant differences in fitness capacities among soccer players (Mendez-Villanueva et al., 2011a; Mujika et al., 2009; Rampinini et al., 2009b).

2.3.3 Movements typical of soccer

The total distance a player covers during a soccer match is ~11,000 m which can range from ~9000 to 12,000 m (Bradley, et al., 2009b; Burgess, Naughton, & Norton, 2006; Di Salvo, et al., 2007; Rampinini, et al., 2007b; Rampinini, et al., 2009a). Of this typically 75 to 85% is covered at low speeds (Bradley, et al., 2009b; Di Salvo, et al., 2007; Mohr, Krustrup, & Bangsbo, 2003; Rampinini, et al., 2007b; Withers, et al., 1982) suggesting the sport is predominantly aerobic in nature. However, during a game a player may complete over 500 high-intensity efforts including high-speed running, sprint, acceleration, change of direction and jump efforts (Bangsbo, Nørregaard, & Thorsø, 1991; Bradley et al., 2009a; Bradley, et al., 2009b; Withers, et al., 1982). Due to the chaotic nature of team-sport (Douge, 1988), players will experience periods of match-play that are more intense than others (Bradley, et al., 2009b; Buchheit, et al., 2010d; Mohr, Krustrup, & Bangsbo, 2003), which may require the repeated performance of these high-intensity efforts. This intermittent yet intense component of the game, indicates a reliance is also placed on the anaerobic system. As the performance of these physically demanding tasks is thought to be critical in the outcome of more crucial moments in the game (Reilly, Bangsbo, & Franks, 2000), research has focused on quantifying these movements (Bradley, et al., 2009a; Bradley, et al., 2009b; Di Salvo et al., 2010; Di Salvo, et al., 2009; Mohr, Krustrup, & Bangsbo, 2003) and investigating the capacity to perform (Krustrup et al., 2003; Krustrup, et al., 2006a; Rampinini et al., 2007a; Rampinini, et al., 2009b), train (Bravo et al., 2008; Buchheit et al., 2010b; Helgerud et al., 2001; Impellizzeri et al., 2006) and recover from, these efforts (Abt et al., 2011; Rowsell et al., 2009).

2.3.4 High-speed running as a measure of physical performance

In the last decade, soccer-based research has focussed on the high-speed movements performed during a game (Bradley, et al., 2009b; Di Salvo, et al., 2009; Rampinini, et al., 2007b; Rampinini, et al., 2009a). This interest stems from the suggestion that the distance covered at high-speed running is a valid measure of physical performance (Bangsbo, Nørregaard, & Thorsø, 1991; Mohr, Krustrup, &

Bangsbo, 2003). High-speed running can discriminate between standard of play with elite players covering a 28% greater distance during a match than their moderate level counterparts and a 11% greater distance in the Yo-Yo Level 1 Intermittent Recovery Test, a test to measure the ability of an individual to perform repeated high-speed running (Krustrup, et al., 2003; Mohr, Krustrup, & Bangsbo, 2003).

The various thresholds that have been applied to define high-speed running have resulted in a range of distances covered during a match (Table 2-2). One of the only studies to scientifically determine an absolute threshold for high-speed running, involved professional soccer players performing a graded exercise test to establish the speed at which they reached the VT_2 (Abt & Lovell, 2009). This measure was chosen to represent a high-speed running threshold as an athlete exercising at an intensity above this point may display an inability to sustain performance (Davis, 1985). Although players differed in the speed at which VT_2 was achieved, the median value from all players was 4.16 $m.s^{-1}$. This value was recommended as an appropriate high-speed running threshold for researchers wanting to use an absolute as opposed to a relative threshold (Abt & Lovell, 2009). Although this recommendation was based on results from a low sample of players (N = 10) the threshold is similar to what has been used to define high-speed running in a number of studies (Table 2-2).

On average the amount of high-speed running a player performs per game is ~2700 m or ~25% of total distance (Table 2-2). If the category very-high speed running is used, this is reduced to ~1000 m and ~9% of total distance (Table 2-2). The match-to-match variability of the distances elite soccer players cover at high speeds has been determined from a large sample size (7281 individual match files, N = 485) using a semi-automated tracking system (Prozone®) (Gregson, et al., 2010). The between-match variation for distances covered at a speed $\geq$ 5.5 $m.s^{-1}$ over three playing seasons, reported as a CV, was 17.7%, increasing to 23.5% when determined over a shorter period of 8 weeks. Playing position also influenced the between-match variability for both movements with significant differences reported between the positions. It is worth noting that the threshold used in this study ($\geq$ 5.5 $m.s^{-1}$) was higher than what is typically used to define high-speed running. As the between-match variability was increased at higher running speeds (CV of 30.8% for sprint distance), less variability may be expected for distances at lower speeds. Another study using a similar tracking system

(Amisco®) determined between-match variation for very-high speed running (≥ 5.5 $m.s^{-1}$) and for high-speed running (Rampinini, et al., 2007b). The CV for distances at ≥ 5.5 $m.s^{-1}$ was 14.4% which decreased to 6.8% for distances at ≥ 4.00 $m.s^{-1}$. The low variation observed in this study may be due to the smaller sample of players (N = 20) and the low number of matches from which variability was determined (two matches played within a week). Despite these discrepancies the high levels of match-to-match variation in high-speed running suggest that a single match observation does not represent the physical capacity of a player (Gregson, et al., 2010). This does not mean that the use of high-speed running is redundant as a measure of physical performance, as physical capacity and physical performance during a game are two separate qualities. However, the relationship between these measures would be of interest to researchers and should be explored in future research.

Table 2-2 Match analysis differences for distances covered and time spent in different movement categories in senior male soccer players

Study	Level/country	N	Method	Classifications ($m.s^{-1}$)			Total distance (m)			% of Total distance (%)			% of Total time (%)		
				HiSR	VHiSR	Sprint	HiSR	VHiSR	Sprint	HiSR	VHiSR	Sprint	HiSR	VHiSR	Sprint
Brooke et al, 1974	English 1st Div.	40	Notation	Subjectively determined			-	-	521	-	-	10.8	-	-	-
Reilly et al, 1976	English 1st Div.	40	Notation/Audio	SL ≥ 1.13m	-	SL ≥ 1.24m	2784	-	974	31.7	-	11.2	-	-	-
Withers et al, 1982	Australian 1st Div.	20	Notation/Video	SL ≥ 1.75m	-	SL ≥ 1.76m	2172	-	666	18.8	-	5.8	-	-	-
Bangsbo et al, 1991	Danish 1st/2nd Div.	14	Video	≥ 4.17	≥ 5.00	≥ 8.33	-	-	-	-	-	-	8.1	2.8	0.7
Rienzi et al, 2000	South American Int.	17	Video	Based on stride frequency			1268	-	345	15	-	4	5	-	1
Mohr et al, 2003	Italian 1st Div. Danish 1st Div.	18 24	Video	≥ 4.17	≥ 5.00	≥ 8.33	2430 1900	- -	650 410	22.4 18.4	- -	6 4	8.7 6.6	4.2 2.8	1.4 0.9
Burgess et al, 2006	Australian 1st Div.	45	CBT	≥ 3.33	≥ 5.00	≥ 6.67	2900	1100	400	28.7	10.9	4	-	-	-
Di Salvo et al, 2007	Spanish 1st Div.	300	Semi-Auto	≥ 3.92	≥ 5.31	≥ 6.39	2701	942	337	23.7	8.3	3.1	-	-	-
Barros et al, 2007	Brazilian 1st Div.	55	Semi-Auto	≥ 3.89	≥ 5.28	≥ 6.39	2859	1128	437	28.6	11.3	4.4	-	-	-
Rampinini et al, 2007	Italian 1st Div.	208	Semi-Auto	≥ 4.00	≥ 5.50	≥ 7.00	2700	893	-	24.6	8.1	-	-	-	-
Rampinini et al, 2009	Italian 1st Div.	416	Semi-Auto	≥ 3.89	≥ 5.28	-	3947	1224	-	36.8	11.4	-	-	-	-
Andersson et al, 2008	Swedish 1st Div.	93*	Video	≥ 4.17	-	≥ 8.33	1870	-	320	18.1	-	3.1	6.9	-	NA
Bradley et al, 2009	English 1st Div.	370	Semi-Auto	≥ 4.00	≥ 5.50	≥ 6.97	2492	905	255	23.3	8.4	2.4	9	2.6	0.6
Lago-Penas et al, 2009	Spanish 1st Div.	127	Semi-Auto	≥ 3.92	≥ 5.31	> 6.39	2647	806	284	22.5	7.4	2.6	-	-	-
Di Salvo et al, 2009	English 1st Div.	563	Semi-Auto	-	≥ 5.50	≥ 7.00	-	908	229	-	-	-	-	-	-
Osnach et al, 2009	Italian 1st Div.	399	Semi-Auto	≥ 4.44	≥ 5.28	> 6.11	1996	1077	531	18.2	9.8	4.8	6.4	3	1.3
Bradley et al, 2010	English 1st Div.	100	Semi-Auto	≥ 4.00	≥ 5.50	≥ 7.00	2745	987	265	25.3	9.1	2.4	9.3	2.7	0.6
Collective mean ±SD	-	-	-	3.99 ±0.26#	5.29 ±0.20#	7.08 ±0.81#	2494 ±631	997 ±130	442 ±143	23.7 ±5.6	9.4 ±1.5	4.9 ±1.2	7.5 ±1.5	3 ±0.6	0.9 ±0.3

HiSR = high-speed running, VHiSR = very-high speed running, Div = division, CBT = computer based tracking, Semi-Auto = semi-automated tracking, SL = stride lengt
NA = not available, SD = standard deviation, * 72 male and 21 female players, # Does not include stride length or stride frequency

While high-speed running may offer a measure of physical performance during competition, its relationship with match performance is more complex. High-speed running distance can characterise differences between successful and unsuccessful teams competing in the same competitive league (Di Salvo, et al., 2009; Rampinini, et al., 2009a). Successful teams cover a greater high-speed running distance when in possession of the ball than less successful teams, but a lower total high-speed running distance (Rampinini, et al., 2009a). These differences may be due to the greater technical and tactical ability of the more successful teams, which allow them to retain possession, evidenced by the greater number of ball involvements than the less successful teams (Rampinini, et al., 2009a). Hence, due to the longer time with the ball the more successful teams are able to not only cover a greater high-speed running distance when in possession than the less successful teams, but also to dictate play. This may force the opposition to spend more time chasing after the ball to regain possession, resulting in a greater total high-speed running distance in the less successful teams.

Although this suggests that a greater technical and tactical ability may be a more important determinant of success than the ability to perform high-speed running, a given team covers a greater high-speed running distance against the best teams in the league (top eight teams at the end of competition) than against the worst (remaining teams within the competition) (Rampinini, et al., 2007b). As a team will compete in a domestic competition and potentially additional knockout competitions against opposition whose ability may vary greatly, they must be prepared to perform greater amounts of high-speed running when required. Therefore it is likely that technical, tactical and physical ability all play a role in team success.

Thus the relationship between high-speed running and match performance can be summarised as follows; i) the ability to perform a greater amount of high-speed running can discriminate between elite and sub-elite standards of play (Mohr, Krustrup, & Bangsbo, 2003), ii) within a competition the more successful teams will perform less high-speed running than less successful teams (Di Salvo, et al., 2009; Rampinini, et al., 2009a), iii) against better opposition a given team is likely to perform a greater amount of high-speed running (Rampinini, et al., 2007b).

High-intensity movements are considered to be crucial actions in soccer (Bangsbo, Nørregaard, & Thorsø, 1991; Reilly, Bangsbo, & Franks, 2000). While the role of high-speed running has been discussed, near maximal speed movements, such as sprinting, are also considered to be important, specifically in determining the outcome of critical match activities (Cometti et al., 2001). The following section will discuss the role of sprinting in soccer.

2.3.5 Sprinting and maximal speed

Early studies on the mechanics of sprint running investigated the speed-time curve representing movement when sprinting from a standing start (Furusawa, Hill, & Parkinson, 1927). Subsequently, sprint running has been divided into segments for practical application including an acceleration, a constant speed and deceleration phase (Volkov & Lapin, 1979). Researchers and sports practitioners assessing sprint performance in team-sports athletes through field-based testing are often interested in only the acceleration phase of sprint running, specifically quantifying the capacity of an individual to accelerate (sprint time over 10 m) and the maximal speed that can be attained (fastest 10 or 20 m sprint time over 40 m from a flying start) (Little & Williams, 2005; Mendez-Villanueva, et al., 2011a; Young et al., 2008). However, in match analysis research, a player is only classified as sprinting for the time they spend above a chosen speed threshold. Therefore, identification of individual sprint efforts in match analysis refers to the number of times a player exceeds the sprint threshold and does not account for the time or distance spent in the preceding acceleration phase. To provide some context of the differences between what is typically considered sprint running, the field-based assessment of sprint performance and the match analysis quantification of a sprint, these measures have been overlayed on a speed curve smoothed from data of a maximal 30 m sprint effort (Góralczyk, et al., 2003) (

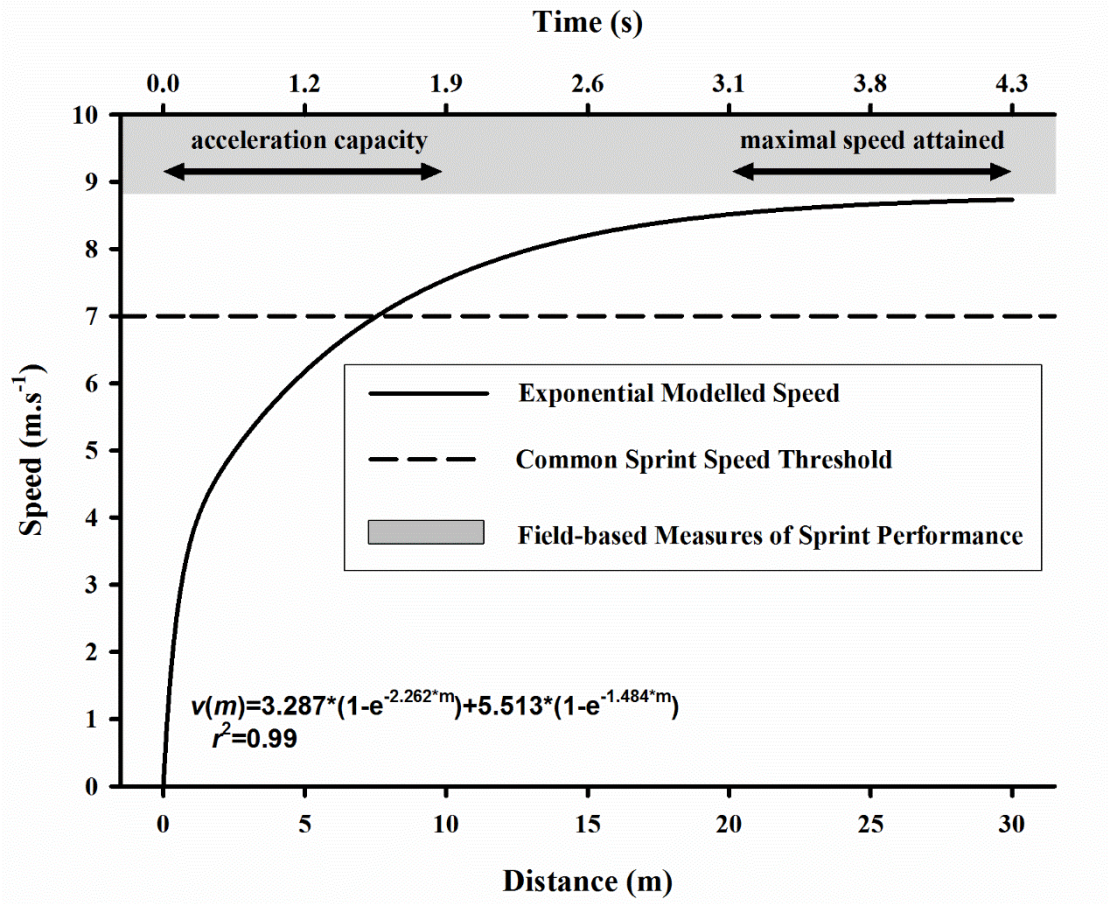

Figure 2-1). To avoid confusion, in this thesis the term sprint effort will be used in the context that it is used in match analysis research (when a player exceeds the designated sprint speed threshold).

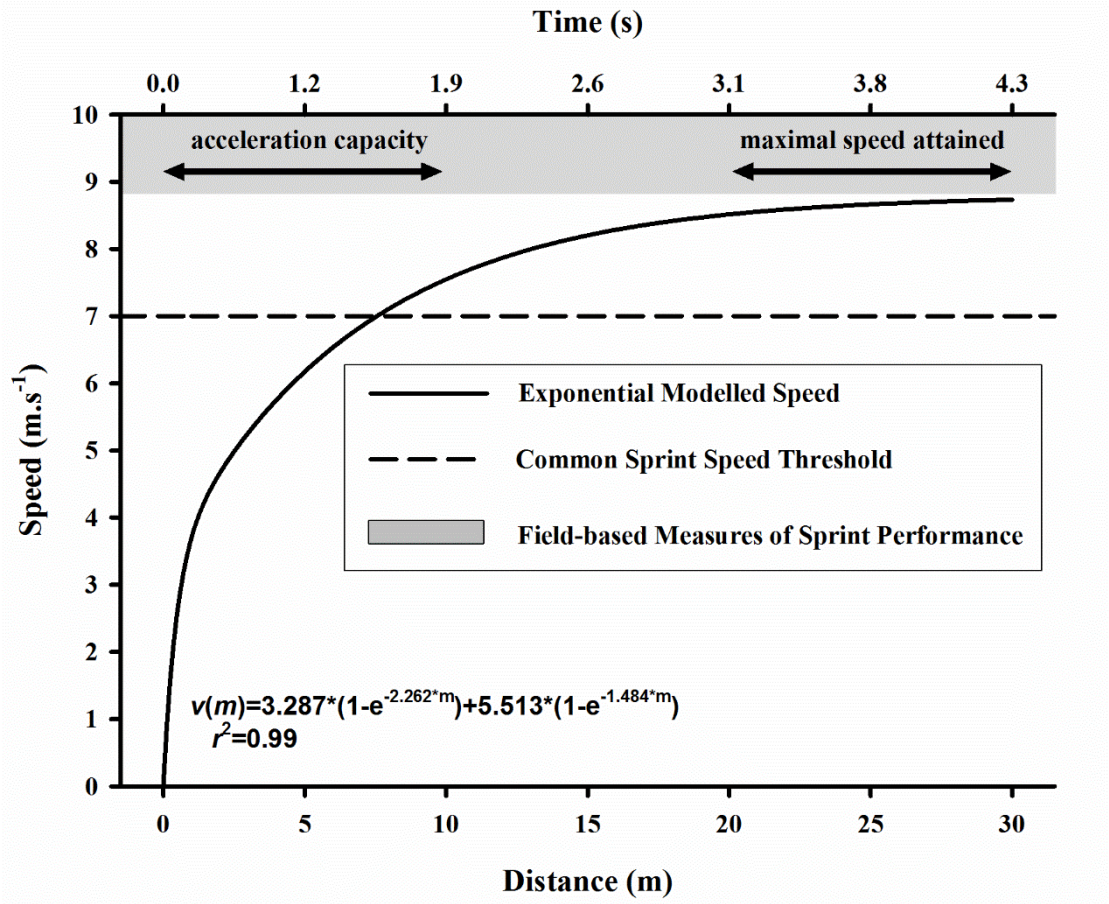

Figure 2-1 Representation of the different contexts of sprint running in terms of field-based assessment of sprint performance and sprint quantification in match analysis overlayed on a 30 m maximal running speed curve for professional soccer players. Speed curve is modelled by a double-exponential function describing speed (*v*) as a function of distance (*m*), (adapted from Góralczyk, et al., 2003). Time is calculated from distance and speed.

In match analysis research, there is a wide variation in the thresholds that have been used to define sprinting (Table 2-2). Regardless of the threshold, sprinting is considered to be a high-intensity movement which occurs close to maximal running speed (Faude, Koch, & Meyer, 2012). On average sprinting constitutes less than 1% of the total time and less than 6% of the total distance a player is moving during a match (Table 2-2). Although sprinting has only a small contribution to the overall movements performed during a game, the sprint effort itself is considered to be an important activity as its performance may be a determinant of match winning actions (Cometti, et al., 2001), such as assisting with or scoring a goal (Faude, Koch, & Meyer, 2012). As the individual time and distance of a given sprint effort is relatively short

(Table 2-3), match analysis research often reports the number of sprint efforts undertaken during a match.

Table 2-3 Match analysis differences for the average number, distance and duration of sprint efforts in senior male soccer players

Study	League/country	N	Method	Classification	No. of efforts	Distance	Duration
Brookes et al, 1974	English 1st Div.	40	Notation	Subjectively determined	52	10.4	-
Reilly et al, 1976	English 1st Div.	40	Notation/Audio	SL ≥ 1.24m	62	-	-
Withers et al, 1982	Australian 1st Div.	20	Notation/Video	SL ≥ 1.75m*	-	22.4*	3.7*
Bangsbo et al, 1991	Danish 1st/2nd Div.	14	Video	≥ 8.33	19	17	2
Mohr et al, 2003	Italian 1st Div. Danish 1st Div.	18 24	Video	≥ 8.33	39 26	- -	2 1.9
Burgess et al, 2006	Australian 1st Div.	45	CBT	≥ 6.67	58	-	-
Di Salvo et al, 2007	Spanish 1st Div.	300	Semi-Auto	≥ 6.39	17	19.3	-
Bradley et al, 2009	English 1st Div.	370	Semi-Auto	≥ 6.97	35	-	-
Di Salvo et al, 2009	English 1st Div.	563	Semi-Auto	≥ 7.00	32	< 20	-
Bradley et al, 2010	English 1st Div.	100	Semi-Auto	≥ 7.00	36	-	-
Di Salvo et al, 2010	Champions League	717	Semi-Auto	≥ 7.00	27	< 20	-
Collective mean ±SD	-	-	-	7.21 ±0.72	37 ±15	18.2 ±4.2	2.4 ±0.9

Div. = division, CBT = computer based tracking, Semi-Auto = Semi-automated tracking, SL = stride length, * = stride + sprinting, SD = standard deviation

In soccer, sprint efforts are performed intermittently throughout a game with the number of efforts ranging from 17 to 58 (Table 2-3). Although this number of efforts appears relatively low in reference to the length of a match, during a game players experience intense periods of play involving greater amounts of high-speed movements than others (Bradley, et al., 2009b; Mohr, Krustrup, & Bangsbo, 2003). Players may also perform multiple sprint efforts interspersed with minimal recovery time (Buchheit, et al., 2010d). Elite level soccer players have faster 10 and 30 m sprint times than amateur players (Cometti, et al., 2001) as well as better repeated-sprint ability (RSA) performance (mean time of six 40 m (2 x 20 m) shuttle sprints) (Rampinini, et al., 2009b). Further, RSA performance is moderately correlated (r = -

0.65) with total match sprint distance in professional soccer players (Rampinini, et al., 2007a). Subsequently, the ability to not only perform, but to repeatedly perform, sprint efforts is considered an important component in soccer.

The physical capacity of a player to sprint is often assessed by their maximal running speed. As the average sprint effort distances in soccer are relatively short (Table 2-3), it is unlikely that maximal speed is regularly attained as athletes do not reach maximal speed until an elapsed distance of 40 – 60 m (Young, Benton, & Duthie, 2001; Young, et al., 2008). It could be argued that in soccer the majority of this distance is covered in the acceleration phase preceding the sprint effort (

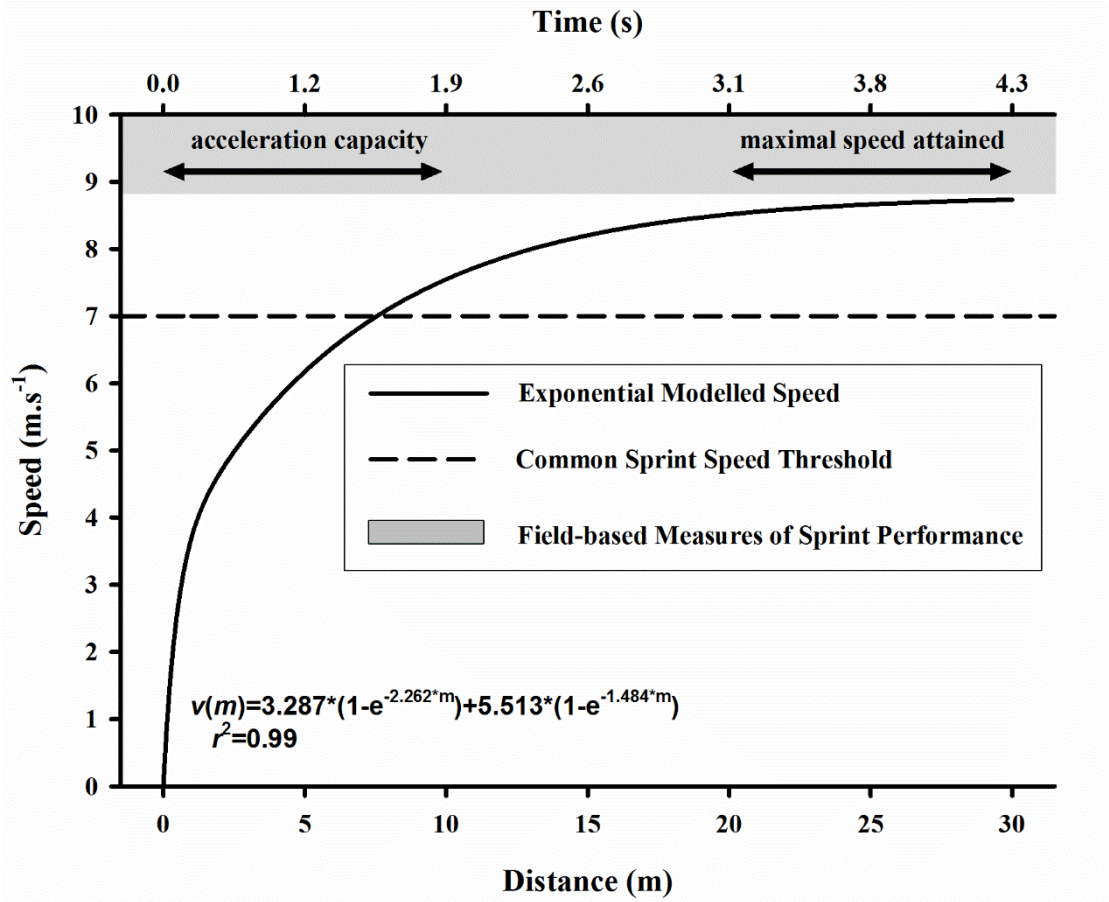

Figure 2-1). However, maximal speed following a flying start is attained after ~29 m (Benton, 2000) or 4 s (Duthie et al., 2006). Finally, when the individual maximal sprint speed (MSS; fastest 10 m split time during a 40 m sprint) of highly trained young (16.7 yrs) soccer players was compared to their peak game speed (Mendez-Villanueva et al., 2011b) players only achieved ~84.4 – 90.5% of MSS. Therefore, maximal speed attained during field-based

testing most likely differs from maximal speed attained during a match. Consequently, this suggests the capacity of a player to rapidly accelerate may be of greater importance than the capacity to reach maximal speed.

The number of sprint efforts undertaken during a match by elite soccer players have been separated into efforts preceded by either a fast or slow acceleration (Di Salvo, et al., 2010; Di Salvo, et al., 2009). Of all sprints only ~30% were preceded by a fast acceleration, however the number of fast accelerations that did not lead to a sprint effort were not reported. Therefore, the quantification of fast or maximal accelerations that are undertaken at a low-speed should be investigated.

The underlying interest in the high-speed movements (high-speed running and sprinting) undertaken by players during a game is that they are considered to be physically hard tasks (Iaia, Rampinini, & Bangsbo, 2009). Subsequently, quantification of these high-speed movements should provide researchers with a measure of the high-intensity work performed by the athlete. However, energetically demanding low-speed actions, such as acceleration, may be also be important to physical performance as they occur frequently throughout a game (Bradley, et al., 2009a). Further, the repeated performance of acceleration in addition to high-speed efforts may have a fatiguing effect on the athlete as the number of acceleration efforts undertaken decrease during elite level team-sports matches (Aughey, 2010). Therefore determining physical performance based solely on high-speed movements may misrepresent high-intensity activity (Little & Williams, 2007).

2.3.6 Acceleration and its role as a high-intensity activity

While many studies have investigated the movement patterns of team sport athletes, based on speed, few studies have investigated the acceleration of athletes during matches (Aughey, 2010; Bradley, et al., 2009a; Osgnach, et al., 2010). This is surprising as the ability to change speed or accelerate (Little & Williams, 2005) is decisive in critical match activities, such as being first to the ball, moving into space before an opponent, and in creating and stopping goal-scoring opportunities (Carling, et al., 2008; Reilly, Bangsbo, & Franks, 2000). The average duration and distance of sprint movements in soccer (Table 2-3) allow insufficient

time and distance to regularly obtain maximal running speed. Therefore, it is likely that a player's ability to accelerate is of greater importance as this will allow them to reach the peak speed achievable, before an opponent.

To accelerate is more energetically demanding than constant-speed movement (Osgnach, et al., 2010). During a maximal 5 s sprint, not only is 50% of the total work achieved within the first 1.5 s, (Cavagna, Komarek, & Mazzoleni, 1971) but a peak power output ($W.kg^{-1}$) 40% greater than the average power output is obtained after only ~0.5 s (Figure 2-2) (di Prampero et al., 2005). This implies that from a standing start the hardest work is performed before the threshold for sprinting is reached (

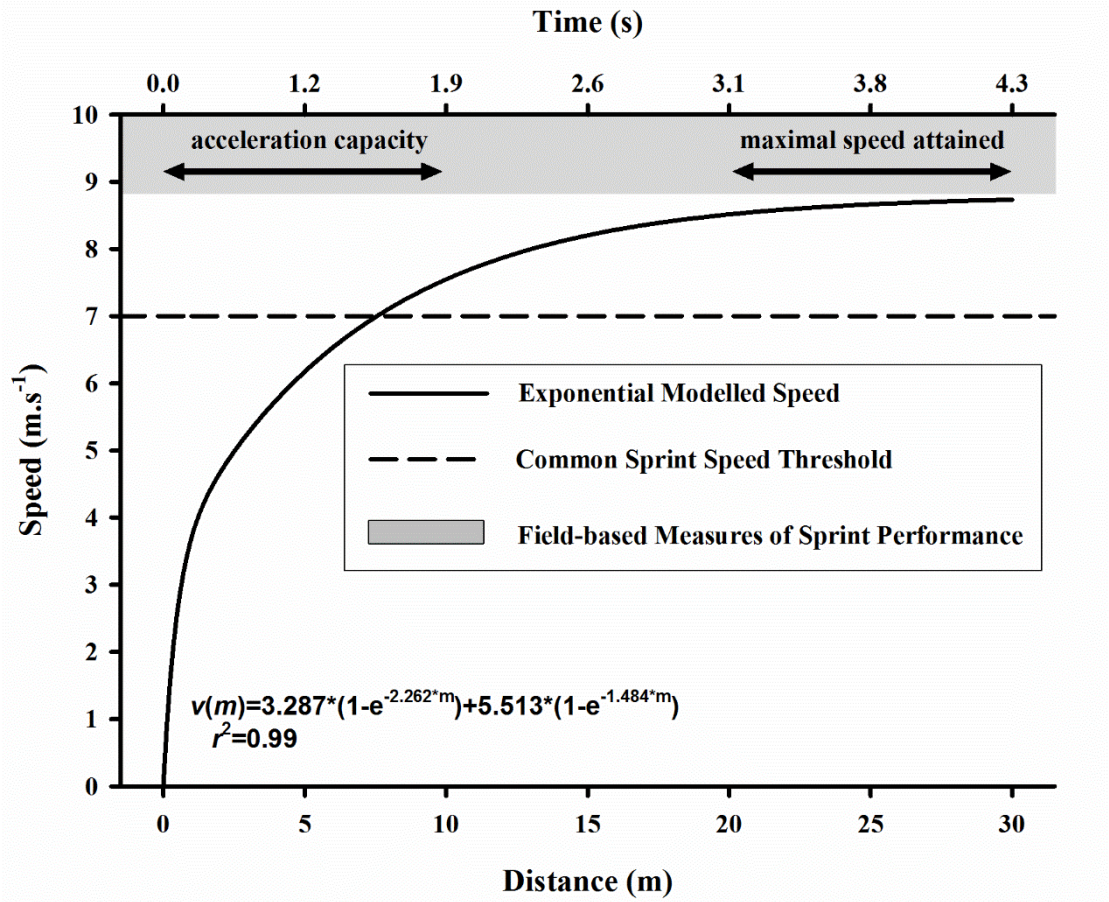

Figure 2-1). Furthermore, although the power output required to run at a constant speed of 4.17 $m.s^{-1}$ is 54% greater than that required to run at a constant speed of 2.5 $m.s^{-1}$ (Figure 2-3), performing an acceleration from the lower speed can match or even exceed the power output required to maintain the higher speed (Osgnach, et al., 2010). Therefore, accelerating is not only a metabolically demanding task, but one that does not need to occur at a high speed to be

challenging. This further supports the need to change the description of high-intensity running to high-speed running (Abt & Lovell, 2009; Gregson, et al., 2010). The practice of excluding accelerations suggests that current match analysis may underestimate the amount of high-intensity that occurs during teams sports where players are required to accelerate frequently (Aughey, 2010; Bradley, et al., 2009a; Osgnach, et al., 2010).

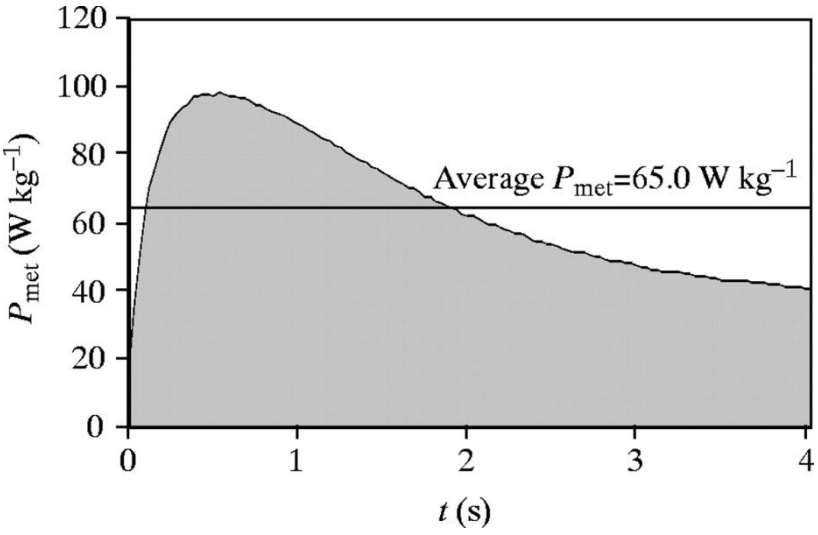

Figure 2-2 Metabolic power P_{met} (W kg^{-1}), as calculated from the product of the energy cost of sprint running and speed, as a function of time t(s) during a maximal effort. Average power over 4 s is indicated by the horizontal line (di Prampero, et al., 2005)

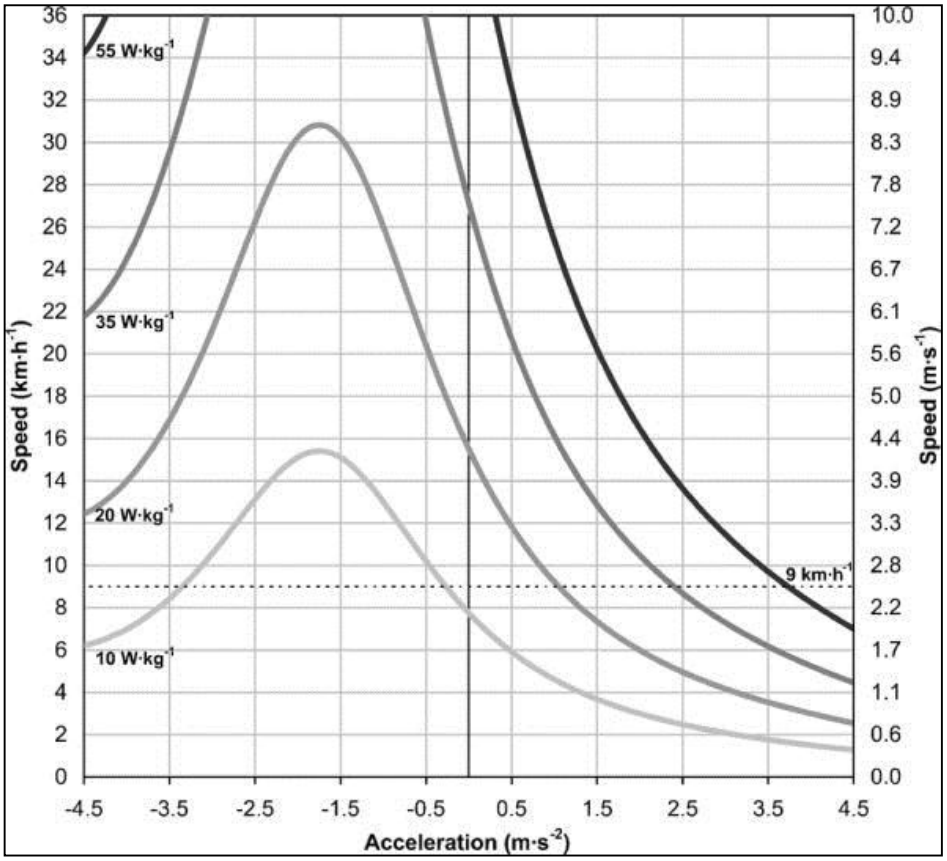

Figure 2-3 Metabolic power output calculated as function of speed (y-axis) and acceleration (x-axis) (Osgnach, et al., 2010)

Changes in speed can occur at a range of speeds; therefore, accelerations need to be categorised based upon their rate of change in speed and expressed in $m.s^{-2}$. Accelerations have been classified as either, moderate (> 1.11 $m.s^{-2}$ (Wisbey, et al., 2010) and 2.5 – 4.0 $m.s^{-2}$ (Bradley, et al., 2009a)) or maximal (> 2.78 $m.s^{-2}$ and 4 $m.s^{-2}$ (Aughey, 2010, 2011b; Bradley, et al., 2009a; Farrow, Pyne, & Gabbett, 2008; Gabbett, Jenkins, & Abernethy, 2012)). World-class sprinters accelerate at a rate of ~6 $m.s^{-2}$ during the first 1 s of a race, with the subsequent maximal rate of acceleration being no greater than 2 $m.s^{-2}$ (Arsac & Locatelli, 2002). Sprinters are assisted in their ability to accelerate by starting blocks, rubber running surface and spiked shoes; moreover, their running techniques differ from team-sport athletes on grass (Sayers, 2000). Therefore, it can be assumed that a maximal threshold of > 4 $m.s^{-2}$ is too high for team-sport athletes (Aughey, 2010). This is evidenced by the low number of

maximal efforts, (~13) (Bradley, et al., 2009a) recorded by elite soccer players when using a threshold of > 4 $m.s^{-2}$ suggesting a lower threshold would be more appropriate.

Accelerations have been determined using semi-automated tracking systems (Bradley, et al., 2009a), although, due to technological limitations, there is a lack of satisfactorily-validated methodologies by which this can be accomplished (Reilly, Drust, & Clarke, 2008). Global positioning system and radio frequency devices may allow for the quantification of acceleration during a game, although validation of a suitable technique is still required. Information on the number of accelerations undertaken throughout a match, the speed a player is moving upon commencement of an acceleration (Aughey, 2010), and the time between these accelerations would give a greater insight into the high-intensity activity undertaken during soccer.

2.3.7 Positional differences in the activity profiles of soccer players

The tactical role of a player can influence the movements performed during a game. Although research comparing the activity profiles of different playing positions have used various terminology when separating players into positional roles, there is a trend for positions to be divided into the following groups; central and wide defenders, central and wide midfielders and forwards (Barros et al., 2007; Bradley, et al., 2009a; Bradley, et al., 2009b; Di Salvo, et al., 2010; Di Salvo, et al., 2007; Di Salvo, et al., 2009; Lago-Peñas et al., 2009; Mohr, Krustrup, & Bangsbo, 2003; Rampinini, et al., 2007b). Though a comparison between studies is difficult due to various methodologies, movement descriptors and position classifications there are some trends apparent.

Central defenders generally cover less total, high-speed running and sprint distance then all other positions (Bradley, et al., 2009b; Burgess, Naughton, & Norton, 2006; Di Salvo, et al., 2007; Di Salvo, et al., 2009; Mohr, Krustrup, & Bangsbo, 2003; Rampinini, et al., 2007b; Reilly & Thomas, 1976; Withers, et al., 1982). The role of the central defender is often limited to defensive duties requiring players to stay within their own half. In contrast, central and wide midfielders typically cover the greatest total distances and greater distances at low and moderate speeds, such as jogging, than other positions (Barros, et al., 2007; Bradley, et

al., 2009b; Di Salvo, et al., 2007; Lago-Peñas, et al., 2009; Rampinini, et al., 2007b). Midfield positions often require players to act as a link between the defence and attack resulting in constant movement up and down the pitch, which would explain the large distances covered (Bangsbo, 1994).

The greatest distance covered at high-speed running is commonly undertaken by positions that have offensive duties, such as forwards, wide and central midfielders and wide defenders (Di Salvo, et al., 2009; Mohr, Krustrup, & Bangsbo, 2003; Rampinini, et al., 2007b; Withers, et al., 1982). The greater high-speed running distances covered by wide compared to central defenders reiterates the restriction of a defensive only position. Unlike central defenders in addition to their defensive obligations wide defenders are also required to move up the pitch and assist with attacking play. The greatest sprint distances and number of sprint efforts are undertaken by wide midfielders and defenders (Bradley, et al., 2009b; Di Salvo, et al., 2010; Di Salvo, et al., 2009; Rampinini, et al., 2007b). Players in these positions are likely to be afforded more space providing more time to accelerate and reach high speeds. Forwards may also perform a high number of sprints (Di Salvo, et al., 2010; Di Salvo, et al., 2009), as their role requires them to regularly evade their opponent and move into space. Conversely, central defenders and midfielders perform a lower number of sprints than other positions (Di Salvo, et al., 2010). In addition central defenders and midfielders typically reach lower maximal running speeds in matches then other positions (Bradley, et al., 2009a; Bradley, et al., 2009b). This may be due to the limited space available to central positions, which may restrict them from consistently reaching high speeds. Further, central midfielders have a greater percentage of total sprint efforts that are of short distances (0-5 m) compared to other positions (Di Salvo, et al., 2010). This suggests that it may be more important for central positions to be able to maximally accelerate than reaching a high speed.

To summarise, in soccer each playing position has its own activity profile. It is believed that the most effective training is that which closely replicates the competitive performance. As such, individualised position specific training would be more appropriate for elite development in soccer players and in developing their tactical responsibilities. To date no

study has investigated the positional differences in the acceleration profiles of soccer players during competition. This information would expand the understanding of high-intensity tasks undertaken by players during a match and assist in determining specific training interventions to improve acceleration in soccer players.

2.4 Improving acceleration in team sport athletes

The ability to maximally accelerate is an important component for team-sport athletes, as previously discussed (section 2.3.6). A variety of training strategies have been utilised to effectively develop the capacity to accelerate including resistance training (Moir et al., 2007) and resisted sprint training (Harrison & Bourke, 2009; Spinks et al., 2007; Upton, 2011). These interventions may improve acceleration performance via several proposed mechanisms including, increasing muscular power (Cometti, et al., 2001; Lockie et al., 2010; Wisløff et al., 2004), altering stride kinematics (Moir, et al., 2007; Murphy, Lockie, & Coutts, 2003) and eliciting neuromuscular adaptations, such as intramuscular coordination (Kristensen, van den Tillaar, & Ettema, 2006). The benefits of these training strategies to improve acceleration capacity are well understood and as such they are commonly used by team-sport conditioning staff (for reviews see Cronin & Hansen, 2006; Young, Benton, & Duthie, 2001). However, the intermittent nature of high-intensity activity during a soccer match, suggests that specific acceleration conditioning should not only improve a player's capacity to accelerate maximally but also to do so repeatedly.

Repeat sprint exercise involves the performance of multiple maximal efforts from a standing start and can closely reflect the intense movements undertaken in soccer via the manipulation of the number and length of repetitions and sets and the duration of interspersing recovery periods. The use of repeat sprint exercise as a training tool has primarily been to increase the capacity to achieve a high sprint speed and the ability to maintain that high speed across multiple efforts (Dawson et al., 1998; Mohr et al., 2007; Serpiello, et al., 2011). As repeat sprint exercise requires an individual to achieve maximal speed from a stationary start within a set time or distance, it is unsurprising that repeat sprint exercise training (RST) can also increase the capacity to accelerate (Table 2-4). Further, RST can improve not only the

capacity to accelerate maximally but the ability to do so across multiple sets of repeat sprint exercise (Serpiello, et al., 2011). This makes RST an attractive option to team-sport conditioning staff, as it would reduce the necessity for separate training sessions to improve these fitness qualities.

Supplement ingestion prior to repeat sprint exercise has been used to enhance performance (Gaitanos et al., 1991; Sweeney et al., 2010). Although the supplementation of a variety of ergogenic agents has received extensive investigation (for a review see Bishop, 2010), the ambiguity of the results leaves definitive performance enhancements inconclusive. The ergogenic effect of sodium bicarbonate ($NaHCO_3$) supplementation has been investigated during exercise at a range of intensities and durations (for reviews see Carr, Hopkins, & Gore, 2011; McNaughton, Siegler, & Midgley, 2008). However, the effects of $NaHCO_3$ ingestion on acceleration and speed during short duration (< 10 s) exercise, are unclear. If supplementation can enhance acute performance then chronic supplementation throughout a training intervention may allow an individual to work at a greater capacity during each session, leading to a greater improvement in performance. The following sections will discuss the improvements in performance associated with RST and the use of supplementation to enhance acute repeat sprint exercise performance.

2.4.1 Repeat sprint training to improve acceleration

2.4.1.1 Defining repeat sprint exercise

Multiple-sprint exercise requires the performance of a number (5 – 15) of brief maximal efforts over a set distance or duration, interspersed with brief recovery periods (Girard, Mendez-Villanueva, & Bishop, 2011; Glaister, 2005). The extensive use of multiple effort exercise in the research setting has led to a number of different protocols varying in effort and recovery duration (Girard, Mendez-Villanueva, & Bishop, 2011; Glaister, 2005; Spencer, et al., 2005). Additionally various terminology has been used to describe the different types of exercise involving multiple effort exercise. Although there is no definitive terminology, clarification is required to avoid confusion in the context of this thesis. Where effort duration

is > 10 s and of a maximal intensity the term ‘all-out’ exercise will be used (Girard, Mendez-Villanueva, & Bishop, 2011), whereas ‘sprint’ exercise will refer to maximal efforts of ≤ 10 s duration. Protocols using interspersing recovery periods of > 60 s will be referred to as ‘intermittent exercise’ (Girard, Mendez-Villanueva, & Bishop, 2011). During intermittent exercise sprint performance is relatively maintained throughout the protocol (Balsom et al., 1992). In contrast, for protocols where the interspersing recovery periods are ≤ 60 s the term ‘repeat exercise’ will be used. Repeat exercise often results in a decrement in performance as the exercise continues (Balsom, et al., 1992; Fitzsimmons et al., 1993). This thesis will focus on the training effects of repeat sprint exercise, which refers to short duration sprints (≤ 10 s), interspersed with brief recovery periods (≤ 60 s).

2.4.1.2 Reliability of repeat sprint exercise performance measures

Repeat sprint exercise has typically been used as a performance test to assess an individual’s sprint performance and the ability to recover and reproduce this performance over successive efforts (for reviews see Bishop, Girard, & Mendez-Villanueva, 2011; Girard, Mendez-Villanueva, & Bishop, 2011; Glaister, 2005; Spencer, et al., 2005). The ability to maintain sprint performance over multiple efforts has been termed repeated-sprint ability (RSA). Depending on ergometry and the protocol employed, repeat sprint exercise allows the measurement of speed, acceleration, power and time. For these measures to be used as an assessment of performance it is important that their reliability during a test protocol be determined. An understanding of the within-subject variation is essential when monitoring test performance as it can affect the precision of estimates of change in a given variable (Hopkins, 2000). The following sections will discuss the reliability of performance measures used to assess repeat sprint exercise performance.

2.4.1.3 Field-based repeat sprint exercise performance measures

When conducted in a field-based setting, sprint time, determined by timing gates, is used to assess repeat sprint exercise performance (

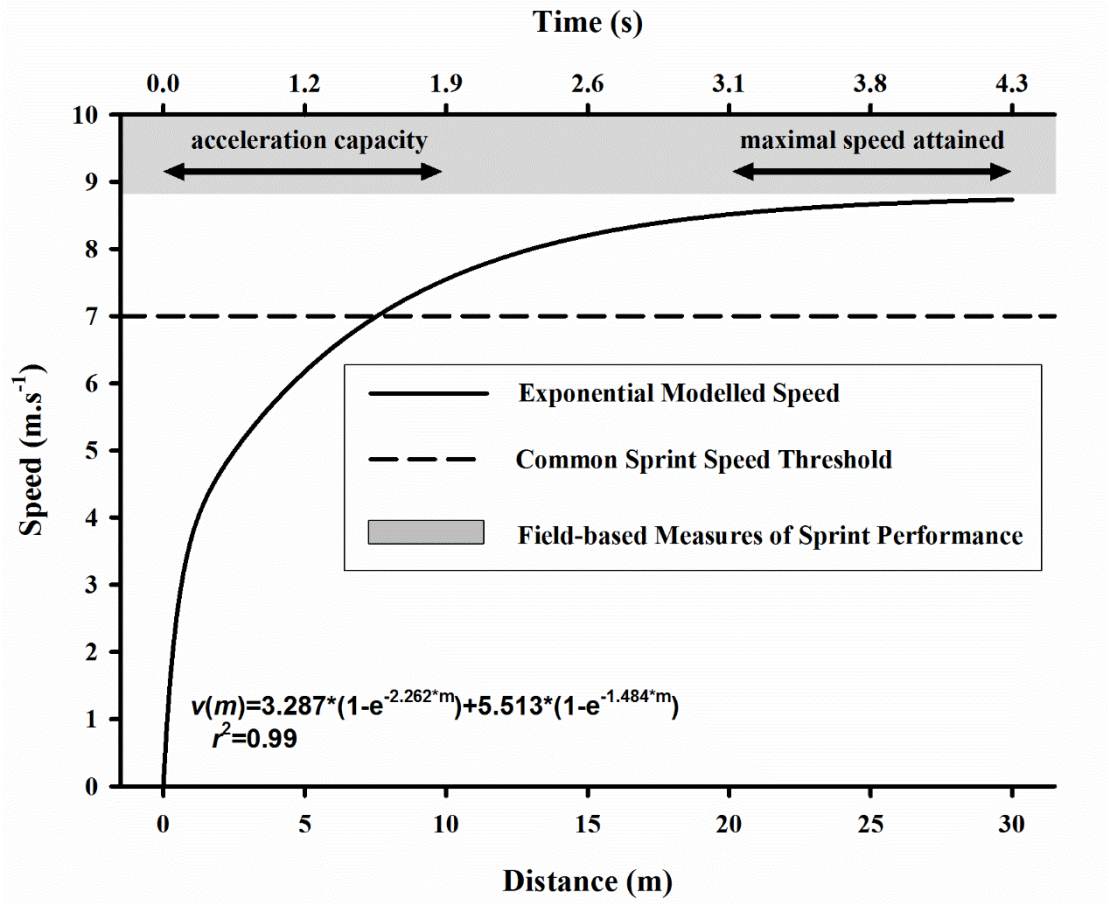

Figure 2-1 and Table 2-4). Measures of fastest and mean sprint times have high reliability (CV; ≤ 2.24) when compared between multiple sessions (Glaister et al., 2007). When assessing an individual's ability to maintain a fast sprint time over multiple efforts the most commonly used measure is total sprint time (sum of all sprint times), which has high test-retest reliability with the Typical Error (TE) ranging from 0.7 – 0.8% (Fitzsimmons, et al., 1993; Spencer et al., 2006).

The most common assessment of an individuals' capacity to accelerate is the time taken to pass through timing gates placed 5 – 10 m apart when commencing from a standing start (

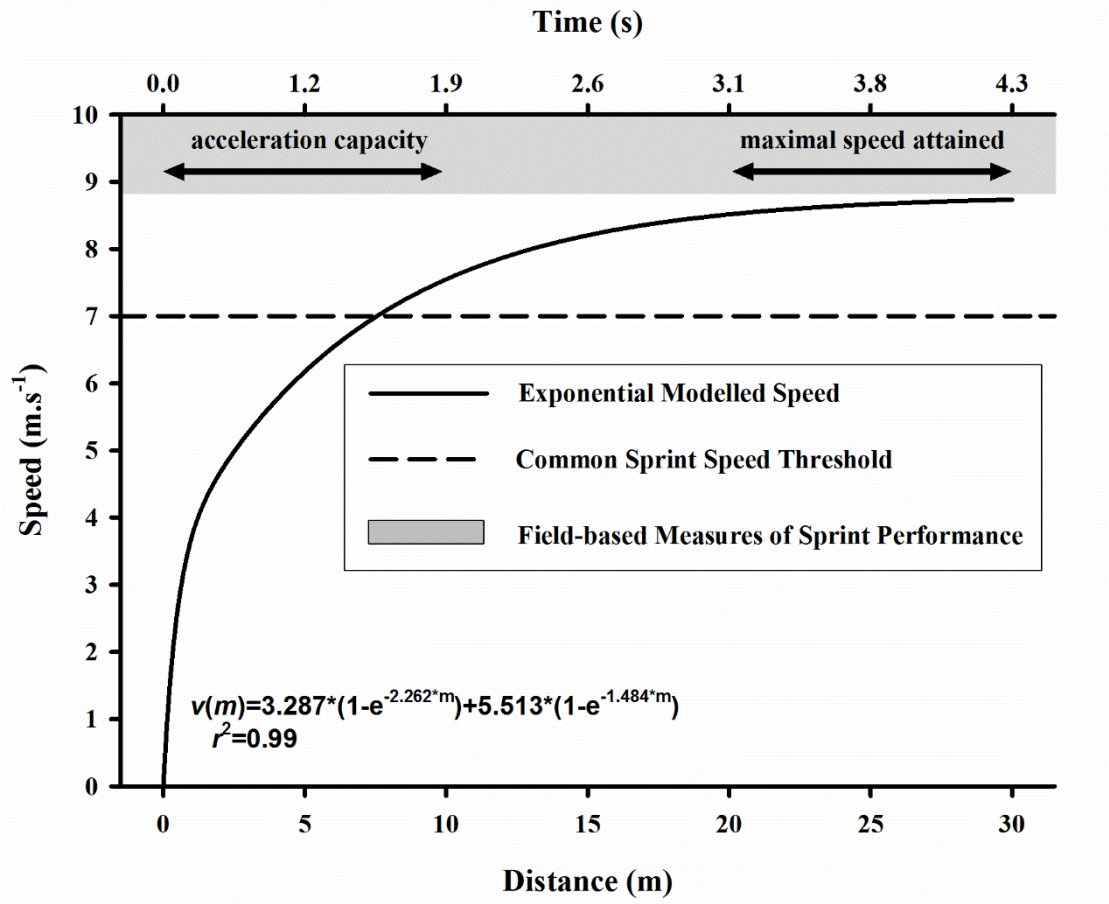

Figure 2-1 and Table 2-4). This measure only represents the average rate of change in speed over this distance. During sprint running the highest rate of acceleration, as measured via a radar sampling at 35 Hz, occurs after 0.2 s (di Prampero, et al., 2005). The time taken for elite soccer players to cover 5 m and 10 m is ~1 s and 1.6 s respectively (Cometti, et al., 2001; Kollath & Quade, 1993), therefore, the assessment of acceleration over this distance is likely to underestimate the true maximal rate of acceleration. This may mask or underestimate the actual improvements in the capacity to maximally accelerate following an intervention. The measurement of instantaneous changes in speed would be more appropriate in determining an individual's true capacity to accelerate.

2.4.1.4 Non-motorised treadmill repeat sprint performance measures

The non-motorised treadmill is a useful tool for the assessment of repeat sprint exercise as it allows an accurate determination of power output generated while sprinting in addition to providing a near-instantaneous measure of running speed (Lakomy, 1987). Further, it can be

used in a lab-based setting providing a closed environment for research that involves invasive procedures not opportune in field-based settings.

Sprints performed on a non-motorised treadmill are determined by their duration as opposed to distance, therefore performance measures differ from those described above. Instantaneous measures of speed ($m.s^{-1}$) and horizontal force (N) can be obtained from the ergometer. In addition power (W) and work (kJ) performed can be calculated from force, speed and sprint duration. Of these, peak and average speed are the most reliable measures, with between-trial and between-day CVs of 1.9 and 1.3%, respectively (Tong et al., 2001). Measures of power are less reliable (CV of $\geq$ 8.2%), which is to be expected as power is a function of speed and force (Tong, et al., 2001). During a repeat sprint exercise protocol involving 4 s sprints, the reliability of these measures reported as a CV were 2.6 and 3.5% for mean and peak speed, and somewhat higher at 4.7 and 10.8% for mean and peak power (Serpiello, et al., 2011). It should be acknowledged that validity and reliability measures of mean speed and distance have been determined for a team sport running simulation on the non-motorised treadmill (Sirotic & Coutts, 2008). However, this protocol was 30-min long and interspersed with low speed running. Thus results from this study are less relevant to this thesis.

A non-motorised treadmill can sample speed at up to 200 Hz, and as such may provide a more accurate assessment of the changes in acceleration capacity following an intervention. However, caution should be taken when interpreting movement data sampled at high frequencies. For example, determining the rate of acceleration over 0.005 s provides information that is of limited practical application. Therefore, to assess acceleration in a way that can be used practically, it should be calculated over a more appropriate period of time. The analysis of speed data from a non-motorised treadmill following a 4 s sprint effort found the rate of change in speed calculated over a 0.5 s period was a better reflection of maximal acceleration than that calculated over a 1 s period as acceleration began to plateau during the latter period (Serpiello, et al., 2011). Therefore, it may be more appropriate to assess maximal acceleration calculated as the average rate of change in speed over a 0.2 to 0.5 s period as this information can be used in a practical manner.

2.4.1.5 Measurements of fatigue during repeat sprint exercise

Fatigue is defined as a transient and recoverable decline in muscle force and/or power with repeated or continuous muscle contractions (McKenna, Bangsbo, & Renaud, 2008). In repeat sprint exercise, fatigue presents as a reduction in any of the aforementioned performance measures with each successive effort. A variety of different calculations have been used to quantify the fatigue experienced during repeat sprint exercise (Glaister et al., 2008; Oliver, 2009). While the performance measures discussed in section 2.4.1.4 demonstrated relatively high reliability, measures of fatigue for both field and lab-based repeat sprint exercise are far less reliable.

One of the first equations used to calculate fatigue during repeat sprint exercise was the percent decrement score (Fitzsimmons, et al., 1993), however, variations of this equation such as the fatigue index (FI) have also been used (Glaister, et al., 2008; Oliver, 2009). The FI calculates the reduction in performance by comparing the best to the worst sprint performed (Equation 1).

Equation 1

$$\left(\frac{Best\ sprint - Worst\ Sprint}{Best\ Sprint}\right) \times 100$$

This measure is problematic as it does not take all sprints into account and can be influenced by a single particularly good or bad sprint (Girard, Mendez-Villanueva, & Bishop, 2011). Further, as individuals have shown an increase in power output or speed during the final sprint of repeat sprint exercise, (Glaister, et al., 2008) the decline in sprint performance is not necessarily linear. Therefore, any measure of fatigue during repeat sprint exercise should take into account the performance of each sprint.

The percentage decrement score is a comparison of actual sprint performance to ideal sprint performance and is often preferred to the fatigue index as it accounts for all sprint efforts (Equation 2). Here, ideal performance is the fastest time or highest work/speed output for a

single sprint multiplied by the number of sprint repetitions, while actual performance is the total time or work/speed output of all sprint repetitions (Fitzsimmons, et al., 1993; Spencer, et al., 2006).

Equation 2

$$\%\ decrement\left(1-\frac{Total\ sprint\ time, work\ or\ velocity}{Ideal\ sprint\ time\ work\ or\ velocity}\right)\times 100$$

Although the percentage decrement score has poor test-retest reliability with a CV of ~32%, when compared to a range of fatigue calculations it is found to be the most valid and reliable quantification of fatigue during repeat sprint exercise (Glaister, et al., 2008). The lack of a reliable calculation of fatigue makes it difficult to assess the performance changes associated with RST.

The use of multiple-sets of repeat sprint exercise on a non-motorised treadmill allows fatigue to be assessed in a different way to that described above. The peak and mean speed, power and acceleration can be determined for each sprint effort (for CVs see section 2.4.1.4) and then an average of each measure can be determined for each set (Serpiello, et al., 2011). Subsequently, each set can then be compared to the next, providing a measure of the fatigue experienced over the entire protocol.

2.4.1.6 Improvements in acceleration performance with repeat sprint training

As sprints are performed from a stationary start during repeat sprint exercise the capacity to maximally accelerate is also likely to be enhanced with RST. When sprint time is used to assess acceleration capacity, relatively small improvements are evident following RST (< 3.2%, Table 2-4). However, larger improvements in acceleration are apparent when sprint speed is used to assess acceleration (> 4.6% Table 2-4). When improvements in acceleration capacity are compared across multiple RST studies (Table 2-4), it appears repeat sprint exercise protocols that involve sprint efforts of ≤ 20 m/< 5 s interspersed by recovery periods of ≤ 30 s are most effective (Buchheit, et al., 2010b; Serpiello, et al., 2011). In contrast, RST that involves changes in direction (e.g. shuttle sprints), seem to be less effective at improving acceleration than purely linear sprint efforts (Table 2-4).

Table 2-4 Improvements in acceleration performance following repeat sprint training

Study	Participants	N	Training Protocol				Adaptations to acceleration	
			Sets/Rest	Reps/Rest	Frequency	Ergometry	10 m Time	Other
Dawson et al, 1998	M, A	9	4-6/ 2-4 min	4-8 x 30 to 80 m sprints/ 30-90 s	3 d/wk for 6 wks	Outdoor running	↓ 3.2% NS (ES=1.00)	NA
Spinks et al, 2007	M, T (rugby/ soccer/AFL)	10	1-2/ 1-2 min	3-6 x 5 to 20 m sprints/ 45-120 s	2 d/w for 8 wks	Outdoor running	NA	↑ 8%** in horizontal hip speed over 0-5 m
Bravo et al, 2008	M, P (soccer)	21	3/ 4 min	6 x 40 m shuttle sprints/ 20 s	2 d/w for 12 wks	Outdoor running	↓ 0.6% NS (ES=0.16)	NA
Buchheit et al, 2008	M, T, Y (handball)	8	1-3/ 2 min	5-5 x 30 to 40 m shuttle sprints/ 14-23 s	2 d/w for 9 wks	Outdoor running	↓ 1.1% NS (ES=0.20)	NA
Buchheit et al, 2010b	M, T, Y (soccer)	10	2-3/ 2 min	5-6 x 15 to 20 m shuttle sprints/ 14-23 s	1 d/wk for 10 wks	Outdoor running	↓ 1.5% (ES=0.07)	NA
Buchheit et al, 2010a	M, T, Y (handball)	7	3-4/ 3 min	4-6 x 5 to 10 m agility/sprints (<5s duration)/ 30 s	2 d/w for 4 wks	Outdoor running	↓ 2.7% (ES=0.60)	NA
Serpiello et al, 2011	M & F, A, U	10	3/ 4.5 min	5 x 4-s sprints/ 20 s	3 d/w for 4 wks	Non-motorised treadmill	NA	↑ 14.7-21.9%* in acceleration (rate of change in speed between 0 and 0.5s)
Lockie et al, 2012	M, T (team sport)	9	4-8/ NA	3-5 x 5 to 20 m sprints/ NA	2 d/wk for 6 wks	Outdoor running	NA	↑ 6.9%* in speed over 0-5 m ↑ 4.6%* in speed over 0-10 m

M = male, F = female, Y = youth (15 – 16yrs), A = active, T = trained, U = untrained, P = professional, NS = not significant, NA = not assessed, ES = Effect size, *Significantly greater than pre-training ($P < 0.05$), **Significantly greater than pre-training ($P < 0.001$)

The use of multiple sets of repeat sprint exercise is more applicable to team-sport performance as the combination of both short (between sprints) and long (between sets) recovery periods are more reflective of what may be undertaken during a match (Serpiello, et al., 2011). After four weeks of multiple-set RST (3 sets of five 4 s sprints interspersed by 20 s, with 4.5 min between sets), an improvement in acceleration of up to 22% was reported in healthy young adults (Figure 2-4) (Serpiello, et al., 2011). Although a greater decrement in acceleration from set 1 to set 3 was experienced post-training, the acceleration during set 3 post-training was still ~15% higher compared to pre-training values. Furthermore, these improvements were accompanied by improvements in both peak and mean speed of up to 6.2 and 7.7% respectively.

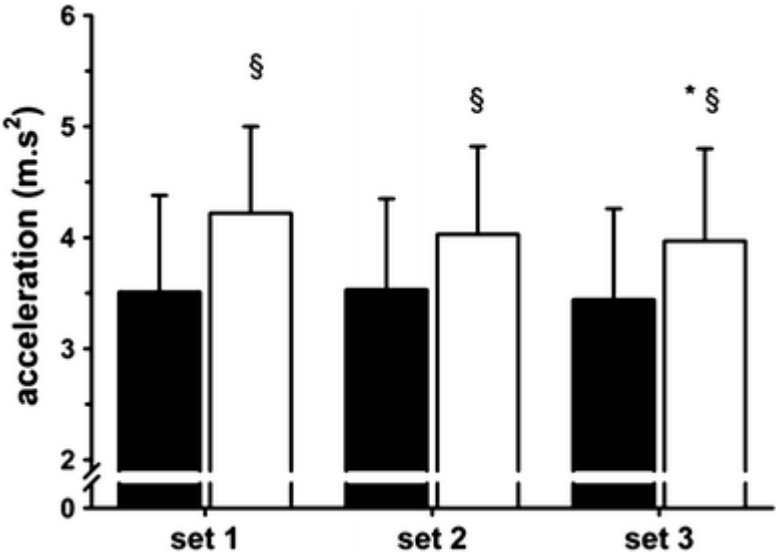

Figure 2-4 Effects of four weeks of multiple-set repeat sprint training on acceleration during repeat sprint exercise (3 sets of 5x4 s sprints interspersed by 20 s recovery with 4.5 min recovery between sets) performed on a non-motorised treadmill. * = Significantly less than set 1 (*P* < 0.05), § = Significantly greater than pre-training (*P* < 0.05), filled bars = pre-training, open bars = post-training (Serpiello, et al., 2011)

Multiple-set RST performed on a non-motorised treadmill can elicit large improvements in the capacity to accelerate and to maintain a high acceleration across multiple sets (Serpiello, et al., 2011). Although this may not be ideal in a team-sport setting, as it restricts the number of individuals who can train at a time, from a research perspective it allows for a detailed

investigation of the performance and physiological changes that may occur in response to a training or supplementation intervention.

The aim of RST is to elicit physiological adaptations that will lead to an enhanced capacity to perform. Therefore, an understanding of the physiological responses associated with the exercise is imperative. The following sections will explore the physiological perturbations that occur during repeat sprint exercise and the potential mechanisms that may lead to fatigue and subsequently limit performance.

2.5 Physiological responses to repeat sprint exercise

2.5.1 Skeletal muscle contraction

Skeletal muscle contraction occurs with the generation of an action potential when voltage-gated sodium (Na^+) channels on the muscle membrane open, resulting in a rapid influx of Na^+ into the cell, which carries a depolarising current (Ruff, 1996a). This causes the muscle membrane potential (E_m) to become less negative, depolarising the cell. At peak voltage the Na^+ channels are rapidly inactivated while voltage-gated potassium (K^+) channels open, leading to an efflux of K^+ out of the cell, which carries a repolarizing current. This causes the muscle membrane potential (E_m) to repolarize to its resting potential. The cellular influx of Na^+ primarily contributes to the upstroke of the action potential, which if sufficient, will lead to the propagation of action potentials along the sarcolemma and into the t-tubular system. The action potential will then activate the voltage sensors dihydropyridine receptors. This triggers the release of calcium (Ca^{2+}) from the sacroplasmic reticulum (SR) via ryanodine receptors into the cytoplasm, increasing [Ca^{2+}]. Calcium then binds to the troponin-tropomyosin complex, resulting in the interaction of the contractile proteins and contraction of the muscle to occur (for a review see Brooks, Thomas, & Kenneth, 2005).

2.5.2 The muscle membrane potential

Ionic regulation is imperative for skeletal muscle contraction due to its role in the maintenance of E_m, excitability and normal muscle function. The E_m is the electrical potential difference across the membrane and is largely influenced by the concentration of intracellular and extracellular K^+ ([K^+]), Na^+ ([Na^+]) and chloride ([Cl^-]) (Table 2-5).

In human skeletal muscle at rest the resting E_m is calculated to be ~-90 mV (Cunningham et al., 1971; Sjøgaard, Adams, & Saltin, 1985). The intracellular $[K^+]$ ($[K^+]_i$) is forty-fold higher than the extracellular $[K^+]$ ($[K^+]_e$), while the extracellular $[Na^+]$ ($[Na^+]_e$) and $[Cl^-]$ ($[Cl^-]_e$) are ~ten and ~five-fold higher than the intracellular $[Na^+]$ ($[Na^+]_i$) and $[Cl^-]$ ($[Cl^-]_i$), respectively (Table 2-5). Movement of these ions down their concentration gradients is accompanied by an electrical charge or current into or out of the cell. The determination of the E_m is primarily credited to the transmembrane K^+ gradient and the high permeability of the muscle membrane to K^+ (Sejersted & Sjøgaard, 2000). As the muscle membrane is far more permeable to K^+ than Na^+, the efflux of K^+ from the muscle repolarises the cell leaving it with a minor negative charge.

Table 2-5 Representation of the different ionic concentrations in various compartments at rest, during and immediately after intense exercise

Compartment	$[K^+]$ (mM)	$[Na^+]$ (mM)	$[Cl^-]$ (mM)	$[HCO_3^-]$ (mM)	pH (pH units)
Intracellular					
Rest	159 (150 – 168)	9 (6-13)	19 (15-22)	-	7.14 (7.08-7.17)
Exercise	131 (129-134)	20 (16-24)	27 (26-28)	-	(6.71 (6.64-6.80)
	ref. 1,2,3	ref. 1,2,3	ref. 1,2	-	ref. 1,2,3
Interstitial					
Rest	4.6 (4.5-4.8)	142	-	-	7.34
Exercise	11.6 (9.5-13.7)	128	-	-	6.98
	ref. 3,6	ref. 3	-	-	ref. 3
Venous Plasma					
Rest	4.2 (3.5-4.8)	141 (139-144)	102 (96 – 105)	28.1 (25.3-30)	7.41 (7.38-7.44)
Exercise	6.0 (4.7–6.7)	148 (145-150)	105 (104-107)	20.5 (15.1-26)	7.20 (6.96-7.33)
	ref. 1,2,3,4,5,6,7	ref. 1,2,4,5,6,7	ref. 1,2,4,5	ref. 4,5	ref. 2,3,4,5,7

Values are the average of mean data from the studies cited (range of mean data in parentheses). Venous data were obtained from the femoral or forearm vein of male participants before, during (last 30 s of all out exercise) and immediately after intense cycling, rowing, treadmill running or incremental one-legged knee extensions of 30 s to 20 min duration. Interstitial data were obtained using microdialysis and intracellular data from muscle biopsies sampled from the vastus lateralis muscle. References: 1) Bergström et al, 1971; 2) Sahlin et al, 1978; 3) Sjøgaard et al, 1985; 4) Medbø et al, 1985; 5) Lindinger et al, 1992; 6) Nielsen et al, 2003; 7) Street et al, 2005. (adapted from Cairns & Lindinger, 2008)

The distribution of Na^+ and K^+ across the muscle membrane is regulated by the sodium-potassium pump (Na^+,K^+-ATPase), an ATP-dependent transport protein. The Na^+,K^+-ATPase transports Na^+ and K^+ against their concentration gradients into and out of the cell respectively, at a 3:2 ratio per cycle, maintaining a high $[K^+]_i$ and a low $[Na^+]_i$ (Clausen, 2003). The rapid movement of these ions across the membrane will alter the electrochemical gradient leading to the depolarization or repolarisation of the E_m. Sufficient E_m depolarization will result in the propagation of action potentials along the sarcolemma and into the t-tubule system leading to skeletal muscle contraction.

The Na^+,K^+-ATPase plays an important role to maintain or to re-establish the resting Na^+ and K^+ concentrations during muscular contraction. During intense exercise there is a rapid efflux of K^+ from the muscle, which exceeds the capacity of the Na^+,K^+-ATPase to reaccumulate K^+. This results in an accumulation of K^+_e leading to an increase in $[K^+]_e$ and a net decline in intracellular $[K^+]_i$ (Kowalchuk et al., 1988; Sjøgaard, Adams, & Saltin, 1985). The inability to maintain K^+ homeostasis during intense exercise is argued to play a significant role in the onset of any fatigue that may occur, and will be discussed further in section 2.5.4.1.

2.5.3 Metabolic pathway contributions to energy production

The ability for the body to perform the necessary muscular work required during exercise is dependent upon the release of energy. The hydrolysis (breakdown of a compound via a reaction with H_2O) of the multifunctional nucleotide, adenosine 5'-triphosphate (ATP), results in the release of adenosine 5'-diphosphate (ADP), inorganic phosphate (P_i) and energy (Brooks, Thomas, & Kenneth, 2005). The ATP content in human skeletal muscle is approximately 20-25 $mmol.kg^{-1}$ dry muscle (dm) (Boobis, Williams, & Wootton, 1982; Dawson, et al., 1998; Gaitanos et al., 1993; Hellsten-Westing et al., 1993). Contraction results in ATP hydrolysis therefore requiring the resynthesis of ATP, which occurs at a maximal rate of approximately 15 $mmol.kg^{-1}$ $dm.s^{-1}$ (Gaitanos, et al., 1993). During maximal exercise skeletal muscle ATP levels are largely preserved, with a 6 s sprint effort resulting in only a small ATP decline of ~13% (Gaitanos, et al., 1993). The relative maintenance and need for replenishment of muscular ATP content provides evidence that metabolic pathways play an important role in ATP production during maximal exercise. The energy pathways that synthesise ATP during exercise are phosphocreatine (PCr) hydrolysis, glycolysis and oxidative metabolism of fats and proteins. The performance of multiple sprint efforts will lead to a change in the contribution of each of these metabolic pathways, which will be discussed in the following sections.

2.5.3.1 Phosphocreatine contribution during single and repeat sprint exercise

At rest intramuscular PCr content is approximately 75-85 mmol.kg^{-1} dm (Bogdanis et al., 1998; Boobis, Williams, & Wootton, 1982; Dawson, et al., 1998; Gaitanos, et al., 1993). During muscular contraction PCr content decrease exponentially with maximal turnover rates of ~9 mmol ATP.kg^{-1} dm.s^{-1} (Hultman & Sjöholm, 1983). In a 6 s sprint effort PCr hydrolysis accounts for approximately 50% of the total anaerobic ATP production (Figure 2-5) (Gaitanos, et al., 1993), which may deplete total PCr stores by ~35-57% (Boobis, Williams, & Wootton, 1982; Dawson et al., 1997; Gaitanos, et al., 1993). The rate of PCr resynthesis post-exercise is sigmoidal with PCr content replenished to 70 and 90% of resting levels at 30 s and 3 min respectively following a 6 s sprint (Dawson, et al., 1997) . Therefore, full restoration of PCr stores following a single 6 s sprint will take in excess of 3 min.

The addition of multiple sprints interspersed by short recovery periods (< 30 s) results in a greater depletion of PCr. Following five 6 s sprints departing every 24 s, PCr content was depleted to 27% of resting levels (Dawson, et al., 1997). Further PCr replenishment after these repeated sprints was slower than that observed after a single sprint with content recovered to only 45 and 80% of resting levels at 30 s and 3 min recovery, respectively. However, despite the greater depletion and slower resynthesis during repeated sprint performance, PCr will still have a significant contribution to ATP resynthesis for all sprints. During repeat sprint exercise on a cycle ergometer (10 x 6 s with 30 s recovery) PCr content decreased to 43 and 16% of the resting level after the first and tenth sprint, respectively (Gaitanos, et al., 1993). However, prior to the tenth sprint PCr content was only 49% lower than resting level and contributed to ~80% of the anaerobic ATP production (Figure 2-5). These results indicate that after a single sprint there is still a considerable contribution from PCr hydrolysis to ATP resynthesis for subsequent sprints.

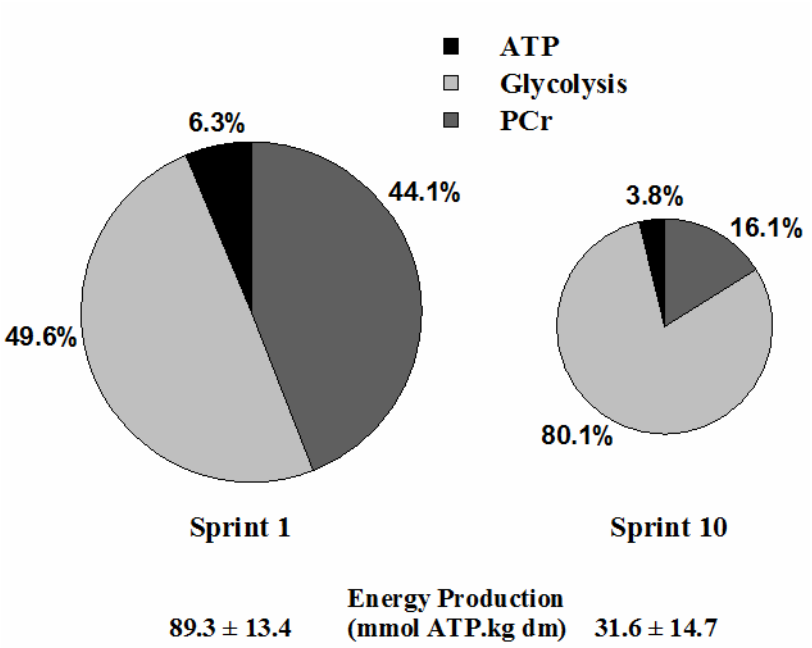

Figure 2-5 Anaerobic adenosine triphosphate (ATP) production during the first and last sprint of ten 6 s sprints interspersed by 30 s recovery (reproduced from Gaitanos et al, 1993). PCr = phosphocreatine

The incomplete restoration of PCr content during repeated sprints with short recovery periods (< 30 s) may compromise the performance of consecutive sprints (Girard, Mendez-Villanueva, & Bishop, 2011). As PCr content is reduced the absolute contribution of PCr to total ATP production is lowered during each successive sprint. In a repeat sprint protocol (10 x 6 s with 30 s recovery) the absolute PCr contribution to ATP synthesis was estimated at 44.3 mmol.kg^{-1} dm for the first sprint, dropping to 25.3 mmol.kg^{-1} dm during the tenth sprint (Gaitanos, et al., 1993). Further, the mean power output during the tenth sprint was only 73% of the initial sprint. Therefore the rapid restoration of PCr may be important for maintaining high-intensity activity, such as those undertaken in team sports, where the recovery time may be insufficient to allow adequate restoration of PCr levels.

2.5.3.2 Glycolysis contribution during single and repeat sprint exercise

The reduction in PCr content during a single sprint effort is somewhat compensated by the increased utilization of glycolysis, resulting in the two systems combining to maintain ATP resynthesis (Glaister, 2005). Glycolysis is the breakdown of glucose and results in the net production of 2 ATP molecules, two pyruvate molecules and two hydrogen ions (H^+) (Brooks,

Thomas, & Kenneth, 2005). Glycolysis is a 10-step process, each step regulated by a specific enzyme. In studies investigating glycolysis it is common to investigate hexokinase, the first step of the glycolytic pathway; glycogen phosphorylase, the enzyme which breaks down glycogen for entry into the glycolytic pathway; phosphofructokinase, the rate-limiting step of glycolysis; and pyruvate kinase, the final step of glycolysis resulting in pyruvate production. Of these, hexokinase, phosphofructokinase and pyruvate kinase also catalyse reactions in one direction, meaning they are non-reversible regulatory steps.

Glycolysis directly produces a limited amount of ATP, but results in the production of pyruvate and reduced nicotinamide adenine dinucleotide (NADH), both substrates available for oxidative phopsphorylation in mitochondria. When glycolysis occurs, NADH subsequently transports H^+ and electrons to the mitochondrial electron transport system, and pyruvate into the mitochondrial matrix for entry into the Krebs' cycle. However, glycolysis can result in production of pyruvate and NADH at a rate which exceeds the capacity of mitochondrial pyruvate uptake and oxidation, typically during high-intensity exercise. As continued ATP production is required during high-intensity exercise. Lactate dehydrogenase can convert pyruvate to lactate, with concomitant oxidation of NADH + H^+ to NAD^+, in times when pyruvate flux exceeds the rate at which pyruvate is able to be oxidised through the electron transport system (Brooks, Thomas, & Kenneth, 2005). This allows continued rapid glycolytic ATP production and also explains the high muscle lactate content that is associated with repeat sprint exercise (Dawson, et al., 1997).

The glycolytic contribution to energy production during multiple sprints is reduced with each successive sprint. During repeated sprints (10 x 6 s with 30 s recovery) glycolysis contributed to 44% of total anaerobic ATP production during the first sprint and only 16% during the tenth sprint (Gaitanos, et al., 1993). It has been suggested that the accumulation of H^+ and resultant drop in pH observed during repeated sprints may be responsible for the reduction in the glycolytic contribution. A low pH can inhibit the enzyme phosphofructokinase (Ui, 1966), a rate-limiting enzyme for glycolysis (Brooks, Thomas, & Kenneth, 2005). However, phosphofructokinase remains active and glycolytic activity is maintained until a drop in pH of

~6.45 (Spriet et al., 1987), well below the normal physiological conditions. A variety of other proposed mechanisms for the reduced glycolytic contribution during repeated sprints have been reviewed elsewhere (Glaister, 2005), and therefore are not a focus of this thesis.

2.5.3.3 Aerobic metabolism contribution during single and repeat sprint exercise

It is difficult to ascertain the aerobic contribution to short duration (< 6 s) sprint efforts due to methodological problems including, the assessment of $\dot{V}O_2$ in working muscle, determination of the size of the active muscle mass and evaluation of the oxygen contribution released from myoglobin (Glaister, 2005). Subsequently, the majority of research investigating the aerobic contribution during repeat sprint exercise has focused on efforts of longer duration (≥ 30 s) than those typically found in team sports.

The involvement of aerobic metabolism during a single sprint effort is minimal (Figure 2-5). During the first 6 seconds of a 30 s maximal effort the rate of ATP turnover by oxidative phosphorylation was calculated at 1.3 $mmol.kg^{-1}$ $dm.s^{-1}$, representing ~9% of total energy produced (Parolin et al., 1999). However, the addition of subsequent sprint efforts interspersed with short recovery periods, results in a decreased ability to produce ATP via PCr degradation and glycolysis (Bogdanis et al., 1996; Gaitanos, et al., 1993; Parolin, et al., 1999). During repeated sprints (5 x 6 s sprints), aerobic ATP delivery is gradually increased and may contribute as much as 40% of total energy supply during the final repetition (Girard, Mendez-Villanueva, & Bishop, 2011). Further, the availability of O_2 is important in the resynthesis of PCr during recovery from high-intensity exercise (Haseler, Hogan, & Richardson, 1999). Therefore, an additional role of aerobic metabolism during repeat sprint exercise may be in the resynthesis of PCr stores during the interspersing recovery periods. However, 8 weeks of repeat sprint training (15 x 6 s sprints interspersed by 1 min recovery) did not alter the rate of PCr resynthesis (Mohr, et al., 2007). In that study, post-exercise PCr stores were measured 3 min following exercise cessation, and it is possible that PCr resynthesis was largely completed (Bishop, Girard, & Mendez-Villanueva, 2011). Therefore,

the relationship between aerobic metabolism and repeat sprint exercise warrants further investigation.

To summarise, each of the various metabolic pathways contributes towards ATP production during repeat sprint exercise. Phosphocreatine degradation has the biggest contribution to energy production during both single and repeated sprint efforts, however both oxidative metabolism and to a lesser extent glycolysis also play a role in ATP resynthesis. The resynthesis of ATP is essential for skeletal muscle contraction to occur as ATP is required to maintain the function of ATPases (e.g. Na^+,K^+-ATPase) and to ensure the unbinding of contractile proteins to allow excitation-contraction coupling to continue.

2.5.4 Muscle fatigue

Muscle fatigue is defined as a transient and recoverable decline in muscle force and/or power with repeated or continuous muscle contractions (McKenna, Bangsbo, & Renaud, 2008).

Fatigue can be divided into two general categories, central and peripheral. Central fatigue refers to fatigue that occurs upstream of the neuromuscular junction (within the higher brain centres or the spinal cord). In contrast, peripheral fatigue refers to fatigue that occurs downstream of the neuromuscular junction (within the muscle). Central fatigue has been defined as a progressive reduction in the voluntary activation of muscle during exercise (Gandevia, 2001). Some of the suggested mechanisms leading to central fatigue during exercise include changes in the neurotransmitter response (Nybo & Secher, 2004) and changes to the perception of effort (St Clair Gibson et al., 2006). The etiology of central fatigue is still inconclusive (for a review see Abbiss & Laursen, 2005; Gandevia, 2001), and while it has been proposed that both central and peripheral fatigue are likely to contribute to overall fatigue (Gandevia, 1998), it is generally agreed that much of fatigue occurs within the muscles (Allen, Lamb, & Westerblad, 2008b).

Peripheral fatigue can result from changes in excitation-contraction coupling, membrane excitability and insufficient metabolic energy supply (for a review see Allen, Lamb, & Westerblad, 2008b; Fitts, 1994). A loss of muscle excitability (the ability of the muscle to initiate and propagate action potentials) can result in the development of fatigue and is related

to the function of voltage gates Na^+ and K^+ channels (Nielsen & de Paoli, 2007). Metabolic factors may also contribute to fatigue such as PCr degradation during high-intensity exercise (Dawson, et al., 1997; Gaitanos, et al., 1993) or reductions in the glycolytic contribution (for a review see Glaister, 2005), potentially limiting ATP production. Other possible factors resulting in peripheral fatigue include an impaired Ca^{2+} release from the SR possibly due to a reduction in action potential amplitude or the accumulation of K^+_e reducing voltage sensor activation (for a review see Allen, Lamb, & Westerblad, 2008a).

In summary, muscular fatigue is thought to be a multifactorial process. Training may elicit changes in each of the suggested mechanisms responsible for peripheral fatigue that will influence the performance and fatigue experienced during repeat sprint exercise. This thesis will explore of role of the ionic disturbances that occur during repeat sprint exercise and whether its manipulation via training and supplementation can enhance performance.

2.5.4.1 Role of extracellular K^+accumulation as a mechanism of fatigue

Ionic perturbations, such as the accumulation of K^+_e and concomitant decrease of K^+_i and increase in Na^+_i, may work synergistically in contributing to fatigue during intense exercise, and can result in muscle membrane depolarization and impaired membrane excitability (McKenna, Bangsbo, & Renaud, 2008).

The majority of studies investigating the effects of fatigue and elevated $[K^+]_e$ on the E_m and force have been conducted *in vitro* using animal fibres (Balog & Fitts, 1996; Balog, Thompson, & Fitts, 1994; Cairns, Flatman, & Clausen, 1995; Westerblad & Lannergren, 1986). The resting E_m in animal fibres is reported between -85 and -75 mV (Balog, Thompson, & Fitts, 1994; Cairns, Flatman, & Clausen, 1995), which is slightly less negative than that measured in human skeletal muscle (Cunningham, et al., 1971). The fatigue elicited by intermittent and continuous muscle contraction is associated with a depolarization of the resting E_m by ~10–15 mV (Balog & Fitts, 1996; Balog, Thompson, & Fitts, 1994; Westerblad & Lannergren, 1986). This reduction is likely due to the reduced intracellular-to-extracellular K^+ ratio that occurs during intense muscle contraction, as an increased $[K^+]_e$ and decreased

$[K^+]_i$ can cause membrane depolarization in unfatigued muscle (Adrian, 1956; Cairns, Flatman, & Clausen, 1995; Cairns et al., 1997).

Depending on its magnitude, depolarization of the resting E_m can result in the slow inactivation of the voltage-gated Na^+ channels (Ruff, 1996b; Ruff, Simoncini, & Stuhmer, 1988). Subsequently, there are less voltage-gated Na^+ channels available that by opening can contribute to the depolarizing Na^+ current which can reduce the action potential amplitude. This may result in a failure to initiate and propagate action potentials at the sarcolemma and t-tubules (Pedersen, de Paoli, & Nielsen, 2005). This loss of excitability is thought to reduce the excitation-induced Ca^{2+} release from the sarcoplasmic reticulum resulting in a lower force production (Nielsen & de Paoli, 2007).

The effects of elevated $[K^+]_e$ on force have primarily been investigated by incubating isolated animal muscle in different K^+ concentrations (Cairns, Flatman, & Clausen, 1995; Cairns, et al., 1997; de Paoli et al., 2007). The muscle is stimulated and the subsequent force produced is expressed as a percentage of the force generated under control conditions, typically $[K^+]_e$ of 4 mM (Cairns, Flatman, & Clausen, 1995; de Paoli, et al., 2007). In rat soleus muscle, the elevation of $[K^+]_e$ to 8 mM only reduced muscle tetanic force to ~90% of control, however, at 11.3 mM $[K^+]_e$, muscle force was reduced to 50% and at 14 mM to ~15% (de Paoli, et al., 2007). A similar trend between elevated $[K^+]_e$ and force depression has been reported in other studies (Cairns, Flatman, & Clausen, 1995; Cairns, et al., 1997; Clausen, Andersen, & Flatman, 1993). Although differences in the force response may vary depending on the type of muscle fibre and the stimulation protocol, these results suggest the increase in $[K^+]_e$ required to substantially reduce force is far greater than the peak plasma $[K^+]$ ($[K^+]_{pl}$) reached by humans during exercise (Table 2.4).

The accumulation of K^+_e during intense exercise may still play an important role in the development of fatigue due to several factors. First, the $[K^+]$ is higher in the muscle interstitium and t-tubule system compared to the plasma (Table 2-5). During intense exercise $[K^+]$ in the muscle interstitium measured with a microdialysis technique may exceed $[K^+]_{pl}$ by as much as 3 – 9 mM (Nielsen et al., 2004; Street et al., 2005). For example, at the point of

exhaustion during one-legged knee extension to fatigue, $[K^+]_{pl}$ increased to ~3.9 mM whereas interstitial $[K^+]$ increased to 13.7 mM (Street, et al., 2005). As a substantial reduction in muscle tetanic force to ~15% of control is observed in isolated muscle incubated in a similar $[K^+]_e$ of 14 mM (de Paoli, et al., 2007), it is possible that large reductions in force may be experienced despite only small increases in $[K^+]_{pl}$. Further, it is thought that the $[K^+]$ in the t-tubules may surpass both $[K^+]_{pl}$ and interstitial $[K^+]$ (Renaud & Light, 1992; Sjøgaard, Adams, & Saltin, 1985), however there is currently no technique that allows the direct measure of t-tubule $[K^+]$ (Juel, 2007). Regardless, an elevated $[K^+]$ in both the interstitium and t-tubule system may lead to a marked force depression during exercise despite lower $[K^+]_{pl}$ (McKenna, Bangsbo, & Renaud, 2008).

Second, the electrochemical gradient is influenced by other ionic disturbances that may accompany an increase in $[K^+]_e$. During fatiguing exercise $[K^+]_i$ can decrease from ~165 to ~129 mM (Sjøgaard, Adams, & Saltin, 1985), if accompanied by an increase in $[K^+]_e$ of 6-7 mM the E_m may drop to ~-60mV, which can result in a substantial depression of force (Cairns, Flatman, & Clausen, 1995). This force depression may be augmented by an increase in $[Na^+]_i$ which causes a decrease in the Na^+_e/Na^+_i gradient. This has been replicated *in vitro* by decreasing the $[Na^+]_e$ at elevated $[K^+]_e$ (Overgaard et al., 1999; Renaud et al., 1996). In rat soleus muscle incubated at $[K^+]_e$ of 9 mM, tetanic force was reduced by 10%, however, when combined with a decrease in $[Na^+]_e$ from 147 to 85 mM, tetanic force was further reduced to 50% (Overgaard, et al., 1999). Small reductions in $[Na^+]_e$ during exercise *in vivo* are masked by the accompanying decrease in plasma volume (McKenna, 1992). However, a reduction in interstitial $[Na^+]$ was observed during exhaustive exercise, while $[Na^+]_{pl}$ increased (Street, et al., 2005). It was theorised that the lower interstitial $[Na^+]$ may be partly due to the activity of Na^+ dependent transport proteins, such as the Na^+/H^+ exchanger, Na^+-HCO_3^- co-transporter and the Na^+-K^+-Cl^- co-transporter that transport Na^+ from the interstitial space into the cell (Street, et al., 2005). The combination of these ionic disturbances during exercise may lower the $[K^+]_e$ at which excitability is reduced. The dose-response curve for the effect of $[K^+]_e$ on peak tetanic force can be seen in Figure 2-6.

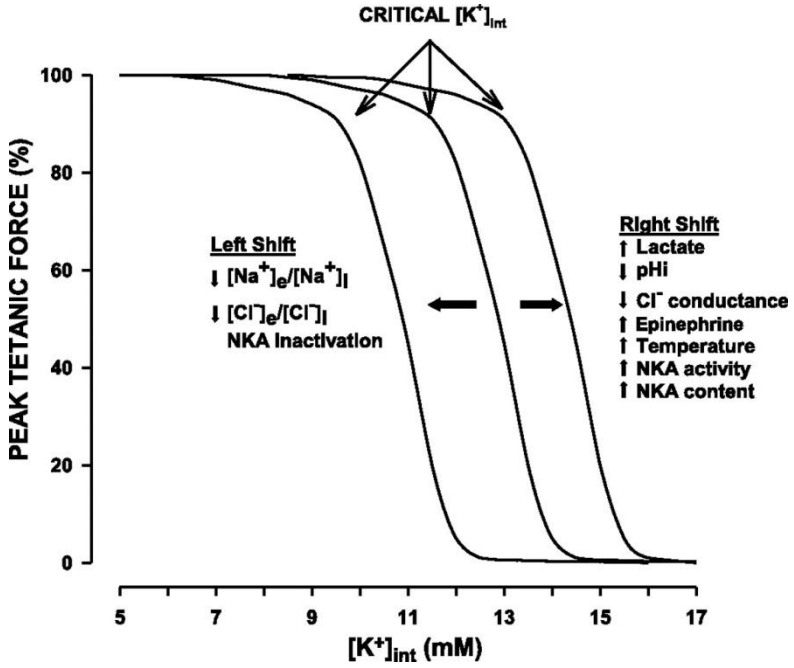

Figure 2-6 Peak tetanic force- interstitial [K^+] relationship in skeletal muscle, indicating the critical interstitial [K^+] the precipitous decline in force, and modulation of relationship by other ions and by the Na^+,K^+-ATPase (NKA). Critical interstitial [K^+] is defined as the interstitial [K^+] at which peak force starts to decrease abruptly (McKenna, Bangsbo, & Renaud, 2008)

Finally, it is important to discuss the practical relevance of the force depression that occurs with elevated $[K^+]_e$ in the context of repeat sprint or acceleration efforts undertaken during soccer. As these actions are maximal efforts, maximal or near maximal rates of force production are essential for their performance. In this regard, even a slight loss of maximal force production (e.g. 10%) could affect performance. As seen in Table 2-4 practically important changes in acceleration with training can be as small as 2.7% (Buchheit, et al., 2010b). Therefore it is likely that even small reductions in the loss of peak force could improve performance. Subsequently, interventions that can either reduce the release of K^+_i or attenuate the increase in $[K^+]_e$ may delay the development of fatigue and enhance performance.

2.5.4.2 Role of the Na^+,K^+-ATPase in attenuating the accumulation of extracellular K^+ during muscular contraction

The Na^+,K^+-ATPase is important in the regulation of Na^+ and K^+ distribution across the plasma membrane during skeletal muscle contraction, and can act to protect against muscle inexcitability caused by K^+ induced depolarization. The largest stimulus eliciting an increase in Na^+,K^+-ATPase activity appears to be muscle excitation (Clausen, 2003; Everts & Clausen, 1994). This is likely due to the rapid influx of Na^+ during E_m depolarization (Nielsen & Clausen, 1997) and subsequent increase in $[Na^+]_i$ which is a powerful stimulator of Na^+,K^+-ATPase activity. Thus, Na^+,K^+-ATPase activity is increased during exercise.

Stimulation of rat soleus muscle following incubation in 10^{-6} ouabain, a glycoside that binds to and inhibits the Na^+,K^+-ATPase, resulted in a greater force depression at raised $[K^+]_e$ (11 mM) compared to control $[K^+]$ (Cairns, Flatman, & Clausen, 1995). Further, with the addition of ouabain, Na^+_i content increased and K^+_i content decreased at elevated $[K^+]_e$ indicating that Na^+,K^+-ATPase activity had been suppressed. In contrast, stimulation following muscle incubation in a range of Na^+,K^+-ATPase stimulators (salbutamol, insulin and calcitonin gene-related peptide), all resulted in an ~26-33% restoration of force at raised $[K^+]_e$, accompanied by a decrease in Na^+_i content and an increase in K^+_i content. These results indicate that Na^+,K^+-ATPase activity is important to restore the Na^+ gain and K^+ loss from the muscle cell during exercise as well as attenuating the depression of force associated with high $[K^+]_e$.

During electrical stimulation of rat soleus muscle, the Na^+,K^+-ATPase may reach its maximal theoretical activity, meaning that all available pumps are activated (Everts & Clausen, 1994). However, this level of Na^+,K^+-ATPase activation is unlikely to occur under physiological conditions (McKenna, Bangsbo, & Renaud, 2008). The maximal *in vitro* activity of the Na^+,K^+-ATPase during intense 'all-out' exercise of < 60 s is reduced by ~12% (Aughey et al., 2006). A depression in maximal Na^+,K^+-ATPase activity during intense exercise could increase the fluxes of Na^+ and K^+ across the plasma membrane during muscular contraction. An increased flux may exceed the capacity of the Na^+,K^+-ATPase to transport and redistribute

Na^+ and K^+ across the membrane (Clausen & Nielsen, 1994), resulting in a depolarization of the resting E_m and a loss of excitability, subsequently accelerating fatigue (Aughey, et al., 2006). The decrease in maximal Na^+,K^+-ATPase activity is likely due to an inactivation of Na^+,K^+-ATPase, rather than a loss of content, which is unchanged following fatiguing exercise (Aughey, et al., 2006; Petersen et al., 2005). Therefore, an intervention to acutely increase Na^+,K^+-ATPase activity during intense exercise may attenuate both the suppression of Na^+,K^+-ATPase activity and the accumulation of $[K^+]_e$. The next section will discuss the ionic disturbances evoked during repeat sprint exercise and the importance of Na^+,K^+-ATPase activity during this type of exercise.

2.5.4.3 Ionic regulation during single and repeat sprint exercise

Numerous studies have investigated the ionic disturbances that occur during intense exercise, but have mostly employed protocols where exercise is either performed to exhaustion or in intermittent bouts of ≥ 30 s duration. Subsequently, the ionic perturbations during single or repeat sprint exercise where effort duration is < 10 s are poorly understood.

The accumulation of K^+_{pl} is greater at higher exercise intensities (Medbø & Sejersted, 1990; Vollestad, Hallen, & Sejersted, 1994), and when a greater active muscle mass is involved (Sejersted & Sjøgaard, 2000). As sprint exercise is of a maximal intensity and involves the use a large exercising muscle mass it is likely that $[K^+]_{pl}$ would be increased during even short duration efforts of < 10 s. The only study to describe the rise in $[K^+]_{pl}$ following a single sprint effort (6 s) reported an increase from ~4.3 mM at rest to ~5.5 mM immediately post sprint (Mohr, et al., 2007). It is seems unlikely that this small increase would result in a depression of force large enough to effect force production in subsequent maximal efforts. However it is possible that the interstitial $[K^+]$ may have been much greater, as it can exceed $[K^+]_{pl}$ during intense exercise (Nielsen, et al., 2004; Street, et al., 2005).

The performance of multiple sprint efforts could lead to a greater rise in $[K^+]_{pl}$ depending on the recovery time between efforts and the number of efforts performed. The aforementioned single sprint was the first of a repeat sprint exercise protocol involving 15 x 6 s efforts

interspersed by 60 s recovery (Mohr, et al., 2007). Interestingly, the increase in $[K^+]_{pl}$ following the 1st sprint to ~5.5 mM was similar following the 5th, 10th and 15th sprint. Similarly, during intermittent all out exercise (4-5 x ≥ 30 s 'all-out' efforts with 3-4 min recovery) the rise in $[K^+]_{pl}$ following the initial exercise bout is similar or slightly reduced following each successive bout (McKenna et al., 1993; Medbø & Sejersted, 1990). The rise in interstitial $[K^+]$ during intermittent one-legged knee extension to exhaustion (3 bouts with 10 min recovery) was similar 1.5 min into each bout (Mohr et al., 2004). Furthermore, the accumulation rate of interstitial K^+ was 85% greater in the initial phase of the first bout compared to the last bout.

A possible explanation for these results is an increase in Na^+,K^+-ATPase activity at the plasma membrane after the initial bout of exercise, resulting in a greater reuptake of K^+ into the muscle during subsequent sprints/bouts (Mohr, et al., 2004). This could suggest that the activity of the Na^+,K^+-ATPase is important in attenuating large increases in both $[K^+]_{pl}$ and interstitial $[K^+]$ when intense exercise bouts are repeated. Thereby, mechanisms to increase Na^+,K^+-ATPase activity during intense exercise may improve K^+ regulation and subsequently enhance performance.

2.5.4.4 Repeat sprint training to improve K^+ regulation

As discussed in section 2.4.1.6, RST has been used to enhance sprint and acceleration performance. Interestingly, RST and intermittent 'all-out' exercise training can also improve K^+ regulation during exercise (Harmer et al., 2000; McKenna et al., 1997; Mohr, et al., 2007). Only one study has investigated the effects of RST on K^+ regulation using a protocol employing efforts of < 10 s duration. After eight weeks of RST (15 x 6 s sprints with 60 s recovery) no difference was observed in $[K^+]_{pl}$ between the first and last training session, despite a significant increase in work of ~6% (Mohr, et al., 2007). Similarly, following seven weeks of intermittent 'all-out' exercise training (4-10 x 30 s maximal efforts with 30 s – 4 min recovery) peak $[K^+]_{pl}$ was unchanged during a maximal 30 s effort, intermittent maximal exercise (4 x 30 s) and exercise to exhaustion (130% $\dot{V}O_{2peak}$), despite 13, 11 and 21%

respectively increased work (Harmer, et al., 2000; McKenna, et al., 1997; McKenna, et al., 1993). Together these results suggest that training involving repeated sprint or 'all-out' efforts may enhance K^+ regulation as evidenced by an increased work production in the face of $[K^+]_{pl}$.

The mechanisms for an enhanced K^+ regulation following training are still unclear. Accompanying an improvement in performance and K^+ regulation following 7 weeks of intermittent 'all-out' training (4-10 x 30 s cycling sprints with 3-4 min rest) was an increase in total Na^+,K^+-ATPase content of 16% (McKenna, et al., 1993). However, other studies have reported an improved K^+ regulation with no change in Na^+,K^+-ATPase content (Kjeldsen, Nørgaard, & Hau, 1990). The measurement of maximal *in-vitro* Na^+,K^+-ATPase activity using the 3-*O*-Methyl fluorescein phosphatase (3-*O*-MFPase) activity assay has been used to determine changes following high-intensity interval training (8 x 5 min cycling intervals at ~85% $\dot{V}O_{2peak}$ interspersed with 1 min recovery) (Aughey et al., 2007). Following training, maximal 3-*O*-MFPase activity increased in muscle at rest and after exercise by 5.4 and 5.6%, respectively, however, as K^+ was not measured it is unknown whether K^+ regulation was also improved post-training. An increase in Na^+,K^+-ATPase isoform protein abundance and improved K^+ regulation has been observed following repeat sprint (Mohr, et al., 2007) and intermittent high-intensity training (Nielsen, et al., 2004). In these studies, it was assumed that the increased individual isoform protein abundance was indicative of an increase in the abundance of functional units and that this may be associated with an increase in Na^+,K^+-ATPase activity (Mohr, et al., 2007; Nielsen, et al., 2004). Taken together, these results suggest that an increase in Na^+,K^+-ATPase activation following training may lead to improved K^+ regulation.

Changes in $[K^+]_{pl}$ following training have been observed to reflect changes in interstitial $[K^+]$ (Nielsen, et al., 2004). If the accumulation of K^+_e can be acutely reduced during training, this may allow an individual to train at a greater capacity over the training period. As such the improvements in both performance and K^+ regulation may be enhanced further than what is

associated with normal training. The ingestion of $NaHCO_3$ prior to exercise has been suggested to increase Na^+,K^+-ATPase activity and subsequently lower the rise in $[K^+]_{pl}$ (Sostaric et al., 2006). The next section will discuss both the metabolic and performance responses to $NaHCO_3$ ingestion prior to exercise.

2.5.5 $NaHCO_3$ supplementation

2.5.5.1 Effects of $NaHCO_3$ ingestion on acid-base status and ionic regulation

A potential mechanism for lowering the accumulation of K^+_{pl} during exercise is through $NaHCO_3$ ingestion (Raymer et al., 2004; Sostaric, et al., 2006). However, the majority of research involving $NaHCO_3$ ingestion has focused on its ability to increase the blood alkalinity (Bishop & Claudius, 2005; Bishop et al., 2004; Costill et al., 1984). Therefore this section will briefly discuss the effect of $NaHCO_3$ ingestion on acid-base status.

The ingestion of $NaHCO_3$ increases the plasma bicarbonate ($[HCO_3^-]_{pl}$) and $[Na^+]_{pl}$. The increase in $[HCO_3^-]_{pl}$ leads to a greater removal of extracellular hydrogen ($[H^+]_{pl}$), by binding with H^+ to form carbonic acid. This dissociates into H_2O and CO_2, with CO_2 excreted at the lungs. The removal of $[H^+]_{pl}$ will increase plasma pH, increasing the blood alkalinity. It is unclear whether $NaHCO_3$ ingestion affects interstitial ionic concentrations. The ingestion of sodium citrate, to increase blood alkalinity, has been found to increase both plasma and interstitial H^+ during exercise compared to ingestion of a placebo substance (Street, et al., 2005). However, further research measuring interstitial ionic concentrations following $NaHCO_3$ ingestion is required. While measures of exercise performance, such as time to fatigue, peak power and total work, have been enhanced following metabolic alkalosis (for a review see McNaughton, Siegler, & Midgley, 2008) the mechanisms by which this may occur are still relatively unknown.

An increase in $[H^+]$ has often been suggested as a major cause of fatigue based primarily on correlations between fatigue development and the accumulation of lactate and decrease in muscle pH (for a review see Cairns, 2006; Nielsen & de Paoli, 2007), however, there is substantial evidence arguing against this theory. First, a low pH of ~6.67 has little or no effect

on the contractile function of mammalian muscle at physiological temperatures (Westerblad, Bruton, & Lannergren, 1997). Second, intracellular acidosis may offer a protective effect on muscle function (Nielsen, de Paoli, & Overgaard, 2001). When isolated muscle is incubated at elevated $[K^+]_e$ resulting in a substantial depression of force, the addition of lactic acid to reduce intracellular pH led to a considerable recovery in excitability and force (de Paoli, et al., 2007; Pedersen, Clausen, & Nielsen, 2003). While acidosis can improve tolerance to elevated $[K^+]_e$, it has been suggested that that this tolerance may be outweighed by the increase in K^+ loss from working muscle (Nielsen & de Paoli, 2007). Together these results, suggest that an increase in H^+ is not a major cause of fatigue, however, both $[H^+]$ and $[HCO_3^-]$ are altered following $NaHCO_3$ ingestion.

To understand the effects of $NaHCO_3$ ingestion on K^+ regulation it is important to discuss other ionic changes that occur following $NaHCO_3$ ingestion. The cell membrane is impervious to HCO_3^- (Wroblewski et al., 2005), as such intracellular $[H^+]$ ($[H^+]_i$) is often reported as unchanged following $NaHCO_3$ ingestion (Bishop & Claudius, 2005; Costill, et al., 1984). However, studies have rarely compared $[H^+]_i$ from pre-ingestion to post-ingestion within the same trial, instead comparing only post-ingestion $[H^+]_i$ following $NaHCO_3$ ingestion to $[H^+]_i$ at the same time point following ingestion of a placebo substance (Bishop, et al., 2004; Stephens et al., 2002). Interestingly, no change in $[H^+]_i$ is generally found in studies that have used sodium chloride (NaCl) as a placebo substance, thus matching the amount of Na^+ ingested with $NaHCO_3$ (Bishop, et al., 2004; Costill, et al., 1984). In contrast, in studies that have used calcium carbonate ($CaCO_3$) as a placebo, an increase in $[H^+]_i$ has been reported following $NaHCO_3$ ingestion (Stephens, et al., 2002). This suggests that $[H^+]_i$ may be reduced by an increase in $[Na^+]_e$ a process that would be masked in studies using a placebo that contains Na^+. The increase in $[Na^+]_e$ would alter the transmembrane Na^+ gradient thus stimulating the Na^+/H^+ exchanger, a membrane transport protein that moves Na^+ into and H^+ out of the cell at a 1:1 ratio, resulting in a reduction in $[H^+]_i$ and an increase in $[Na^+]_i$ (Aickin & Thomas, 1977). As $[H^+]$ leaves the cell it binds with HCO_3^- and is removed, leading to an increase in both intracellular and extracellular pH following $NaHCO_3$ ingestion. However, the

increase in $[Na^+]_i$ is of particular interest as can stimulate Na^+,K^+-ATPase activity, thus increasing the reuptake of K^+ into the cell and attenuating the accumulation of $[K^+]_e$ (Lindinger et al., 1999; Sostaric, et al., 2006).

2.5.5.2 Effects of $NaHCO_3$ ingestion on K^+ regulation at rest and during acute exercise

The effects of $NaHCO_3$ ingestion on $[K^+]$ regulation remain equivocal. The perturbation in venous $[K^+]_{pl}$ under resting conditions following $NaHCO_3$ ingestion is shown in Figure 2-7. Specifically, there was an initial non-significant rise in $[K^+]_{pl}$ between 30 to 70 min, which was similar to pre-ingestion values at 80 min. This was followed by a greater reduction in $[K^+]_{pl}$ which was significantly lower than pre-ingestion values at 160 min (3.52 vs 4.02 mM) (Lindinger, et al., 1999). Other studies have assessed the effects of $NaHCO_3$ ingestion on $[K^+]_{pl}$ by comparing values to those when a placebo substance is ingested (Raymer, et al., 2004; Siegler et al., 2010). At rest, $[K^+]_{pl}$ sampled from the antecubital vein was 0.4 mM lower at 75 (Raymer, et al., 2004) and 180 min (Sostaric, et al., 2006) following $NaHCO_3$ ingestion compared to placebo. In contrast, no difference in arterialized-venous $[K^+]_{pl}$ sampled from the dorsal vein of the hand was found at rest 120 min after $NaHCO_3$ ingestion compared to placebo (Stephens, et al., 2002). The ingestion of $NaHCO_3$ was found to increase the efflux of K^+ from the forearm muscle at fatigue and 10 min into recovery following exhaustive exercise (Sostaric, et al., 2006). An increased efflux of K^+_i may explain the initial rise in $[K^+]_{pl}$ following $NaHCO_3$ ingestion under resting conditions (Lindinger, et al., 1999), and suggests an increased opening of K^+ channels (Sostaric, et al., 2006). However, as it has not been directly measured it is unclear whether alkalosis causes a greater efflux of K^+_i at rest.

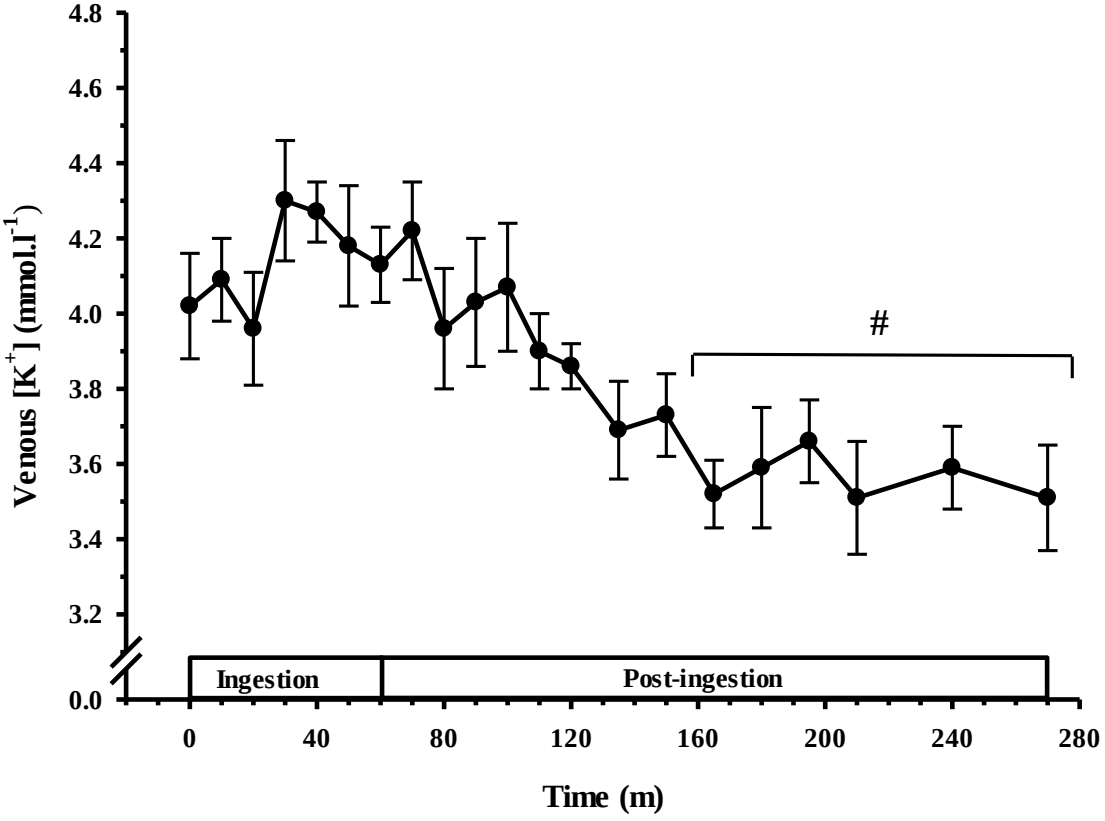

Figure 2-7 Changes in venous $[K^+]_{pl}$ sampled from the antercubital vein following ingestion of 3.57 mmol.kg^{-1} of $NaHCO_3$ ingested at 10 min intervals over 60 min (reproduced from Lindinger, et al., 1999)

Several studies have reported a lower $[K^+]_{pl}$ during exhaustive exercise following $NaHCO_3$ ingested 180 and 90 minutes prior to exercise (Raymer, et al., 2004; Sostaric, et al., 2006). In both studies, $NaHCO_3$ ingestion resulted in an improvement in exercise performance (greater time to fatigue). During 'all-out' intermittent exercise (3 x 30 s maximal efforts interspersed by 180 s recovery performed on a non-motorised treadmill) capillary sampled $[K^+]_{pl}$ was significantly lower following $NaHCO_3$ ingestion after 150 s recovery following each effort (Siegler, et al., 2010). However, an improvement in performance compared to placebo ingestion was only evident when $NaHCO_3$ ingestion was accompanied by an active recovery as opposed to a passive recovery. In contrast, ingestion of $NaHCO_3$ 120 min prior to exhaustive cycling exercise did not change arterialised-venous $[K^+]_{pl}$ throughout the protocol or improve performance (Stephens, et al., 2002).

It is still unclear as to the potential mechanisms that may reduce $[K^+]_e$ at rest or during exercise following $NaHCO_3$ ingestion. It has been suggested that the increase in $[Na^+]_i$ may stimulate Na^+,K^+-ATPase activity resulting in a greater re-uptake of K^+ into the muscle, thus, lowering K^+_e accumulation (Lindinger, et al., 1999; Sostaric, et al., 2006). Following $NaHCO_3$ ingestion the K^+ efflux from muscle was 49% greater at the end of exercise during dynamic finger flexion when compared to $CaCO_3$ ingestion (Sostaric, et al., 2006). Despite this greater efflux, $[K^+]_{pl}$ was significantly lower throughout exercise and recovery. Further, a greater re-uptake of K^+ into muscle was experienced at fatigue and for 10 min into recovery. These results, in addition to the eventual reduction in $[K^+]_{pl}$ at rest following $NaHCO_3$ ingestion (Lindinger, et al., 1999) suggest $NaHCO_3$ supplementation may increase Na^+,K^+-ATPase activity. As discussed in section 2.5.4.2 this may be due to the increase in $[Na^+]_i$, following $NaHCO_3$ ingestion. Interestingly, stimulation of isolated rat muscle exposed to $[HCO_3^-]_e$ of 20 and 40 mM did not change the K^+ efflux from the muscle or in the loss of force when HCO_3^- was elevated (Broch-Lips et al., 2007). This would support the idea that it is the increase in Na^+ rather than HCO_3^- following $NaHCO_3$ ingestion that may affect K^+.

2.5.6 Ingestion of $NaHCO_3$ to enhance repeat sprint exercise performance

The ingestion of $NaHCO_3$ prior to exercise to enhance performance has received substantial investigation (for a review see McNaughton, Siegler, & Midgley, 2008), however different responses have been reported depending on the type of exercise and the ingestion protocol employed. The ingestion of $NaHCO_3$ invokes several physiological responses at rest and during exercise (see sections 2.5.5.1 and 2.5.5.2). This section will focus on the performance enhancing effects of $NaHCO_3$ ingestion prior to repeat sprint exercise.

While a large number of studies have investigated the effects of $NaHCO_3$ ingestion on intermittent 'all-out' exercise, few have used an exercise protocol where the duration of each repetition is $\leq$ 10 s (Table 2-6). Further, these studies provide conflicting results on the potential performance enhancing effects of pre-exercise $NaHCO_3$ ingestion.

Table 2-6 Improvements in repeat sprint exercise following sodium bicarbonate ingestion

Study	Participants	N	Exercise Protocol	Dose ($g.kg^{-1}$)	Ingestion Protocol	Placebo	Ergogenic effect
Lavender et al, 1989	M, F, A	23	10 x 10 s cycle sprints with 50 s recovery	0.3	Two even doses at 120 and 60 min prior to exercise	NaCl	~1.2% ↑* in mean power No difference in peak power
Gaitanos et al, 1991	M, A	7	10 x 6 s sprints on NMT with 30 s recovery	0.3	One dose over 10 min, 160 min prior to exercise	NaCl	No difference in peak and mean power and peak and mean speed
Bishop et al, 2004	F, A	10	5 x 6 s cycle sprints departing every 30 s	0.3	One dose 90 min prior to exercise	NaCl	5.1% ↑* in total work ~4.1% ↑* in peak power
Matsuura et al, 2007	M, A	8	10 x 10 s cycle sprints with 360 s recovery before 5^{th} and 9^{th} sprint and 30 s recovery between all other sprints	0.3	Six even doses every 10 min, 120 min prior to exercise	$CaCO_3$	No difference in peak and mean power
Siegler et al, 2012	M, A	8	10 x 10 s sprints on NMT with 50 s recovery (40 s active/10 s passive)	0.3	One dose over 15 min, 60 min prior to exercise 120 min prior to exercise 180 min prior to exercise	NA	No difference in peak and mean power and peak and mean speed between

M = male, F = female, A = active, NMT = non-motorised treadmill, NaCl = sodium chloride, $CaCO_3$ = calcium carbonate, NA = not assessed, *Significantly greater than placebo ($P < 0.05$)

The ingestion of $NaHCO_3$ prior to exercise has been reported to increase total work and peak and mean power during repeat sprint exercise performed on a cycle ergometer (Bishop, et al., 2004; Lavender & Bird, 1989). However, it is difficult to make inferences of this improvement in performance to team sports, as they may not translate to improvements in running performance. During repeat sprint exercise (10 x 6 s sprints with 30 s recovery) performed on a non-motorised treadmill, there was no significant increase in peak and mean power and speed or total work following $NaHCO_3$ supplementation (Gaitanos, et al., 1991). However, there was a trend for a higher mean power (0-5.9%), peak power (1-8.4%) and total work done (2%) following $NaHCO_3$ ingestion compared to placebo. It should be acknowledged that prior to each sprint participants were instructed to attain a running speed of 2.22 $m.s^{-1}$ for 6 seconds (Gaitanos, et al., 1991). As such, the assessment of acceleration was not possible. The only other study to investigate $NaHCO_3$ ingestion on repeat sprint exercise using running ergometry, compared the different timing of $NaHCO_3$ ingestion on performance (Siegler et al., 2012). However the effects of $NaHCO_3$ ingestion were unable to be determined as there was no control group. In summary, the effects of $NaHCO_3$ ingestion on the performance of acceleration and speed during repeat sprint exercise still remain unresolved.

2.5.6.1 The combination of $NaHCO_3$ ingestion and repeat sprint training may lead to greater improvements in performance

A loss of muscle excitability and subsequent depression of force during intense exercise can arise from a combination of elevated $[K^+]_e$, and reduced $[Na^+]_e$ and $[K^+]_i$ (see section 2.5.4.1). Further, even a small reduction in force may affect the ability to maximally accelerate and reach high speeds during repeat sprint exercise. The ingestion of $NaHCO_3$ can attenuate these ionic disturbances during exercise and recovery, potentially enhancing performance (see section 2.5.5.2 and 2.5.6). Subsequently ingestion of $NaHCO_3$ prior to repeat sprint exercise may delay the development of fatigue and improve the ability of an individual to produce maximal acceleration efforts throughout the protocol. As repeat sprint training can improve

the capacity to maximally accelerate and reach a high speed (section 2.4.1.6), the combination of $NaHCO_3$ ingestion and RST could potentially lead to greater post-training improvements in performance. Therefore, future research should investigate this combination of supplementation and training.

2.6 Aims and hypothesis

2.6.1 Aims

The aim of this thesis was to quantify the acceleration profiles of elite soccer players during competition using a valid and reliable tracking device. A further aim was to investigate the efficacy of two interventions to enhance acceleration performance.

2.6.2 Study 1 (Chapter 3)

This study assessed the validity and reliability of 5 and 10 Hz GPS for measuring instantaneous speed during acceleration, deceleration and constant motion.

The hypotheses for this study were that:

1. Both 5 and 10 Hz GPS would provide an acceptable level of measurement for the detection of instantaneous speed.
2. The 10 Hz GPS would provide a greater precision in the measurement of instantaneous speed than its 5 Hz counterpart.

2.6.3 Study 2 (Chapter 4)

The aim of the second study was to quantify the high-intensity movements of elite Australian soccer players during match play with specific reference to acceleration.

Specific hypotheses tested were that:

1. The majority of maximal accelerations undertaken in soccer would be commenced from low speeds.
2. The number of maximal accelerations performed in soccer would exceed the number of sprint efforts.
3. Different positional roles would exhibit specific acceleration profiles.

2.6.4 Study 3 (Chapter 5)

The final study investigated the effects of sodium bicarbonate ingestion during repeat-sprint training to improve acceleration performance.

Specific hypotheses tested were that:

1. The ingestion of $NaHCO_3$ prior to exercise would enhance acceleration performance during repeat sprint exercise.
2. The ingestion of $NaHCO_3$ prior to exercise would attenuate the increase in K^+_{pl} during repeat sprint exercise.
3. The ingestion of $NaHCO_3$ prior to each training session during repeat-sprint training would result in greater improvements in acceleration performance compared to ingestion of a placebo.

CHAPTER 3. STUDY 1: VALIDITY AND RELIABILITY OF GPS FOR MEASURING INSTANTANEOUS VELOCITY DURING ACCELERATION, DECELERATION AND CONSTANT MOTION

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3.1 Introduction

The ability to increase speed or accelerate (Little & Williams, 2005) is decisive in critical activities, such as being first to the ball, moving into space before an opponent and creating and stopping goal scoring opportunities during team sport (Carling, et al., 2008; Reilly, Bangsbo, & Franks, 2000). To accelerate is more energetically demanding than constant speed movement (Osgnach, et al., 2010), but there is currently no satisfactorily validated method for the measurement of accelerations in team sport (Reilly, Drust, & Clarke, 2008). Decelerations are just as common as accelerations in team sports (Osgnach, et al., 2010; Spencer, et al., 2004) and can place significant mechanical stress on the body (Thompson, Nicholas, & Williams, 1999). The eccentric muscle actions required to decelerate can lead to exercise–induced muscle damage, ultimately limiting an athlete's physical performance (Howatson & Milak, 2009). Quantification of the acceleration and deceleration demands of team-sport would add great value to the existing body of knowledge if a satisfactory measurement tool was available. Little is known about the ability of GPS to measure these qualities.

The use of GPS technology to quantify the physical demands of team-sports athletes is now commonplace during training and match-play (Aughey, 2010; Brewer, et al., 2010; Coutts et

al., 2010; Duffield, Coutts, & Quinn, 2009; Farrow, Pyne, & Gabbett, 2008; Wisbey, et al., 2010). Running speed and acceleration efforts are often reported using user-defined speed thresholds (Aughey, 2010; Farrow, Pyne, & Gabbett, 2008; Wisbey, et al., 2010). However, to date only GPS sampling at 1 and 5 Hz has been used (Aughey, 2010; Brewer, et al., 2010; Coutts, et al., 2010; Duffield, Coutts, & Quinn, 2009; Farrow, Pyne, & Gabbett, 2008; Wisbey, et al., 2010), and 10 Hz GPS units are now commercially available. According to the manufacturer, these units have both an increased GPS sample rate and an updated chipset that provides a more sensitive GPS receiver and improved algorithms for determining position. Comparison between 1 Hz and 5 Hz GPS for measuring distance have reported an increased accuracy and improved reliability with greater sampling frequencies (Jennings, et al., 2010a) with even further improvement when using a 10 Hz sampling frequency (Castellano et al., 2011).

The reliability and validity of superseded GPS devices, such as the MinimaxX V2.0 – V2.5, for measuring team sport running activities has recently been established (Coutts & Duffield, 2010; Gray, et al., 2010; Jennings, et al., 2010a, 2010b). Each of these studies compared GPS distance to known distances either pre-measured or derived from timing gates. The reliability and validity of these units was acceptable for measuring longer efforts, but limited for the assessment of brief, high-speed straight line running, accelerations or efforts involving a change of direction (Jennings, et al., 2010a). Another study reported the ability of GPS to assess mean speed when passing through timing gates during a team sport circuit as adequate (MacLeod, et al., 2009). Finally, GPS was found to underestimate mean and peak speed during court-based team sport movement patterns compared to that determined by a high-resolution motion analysis device (VICON) (Duffield, et al., 2010). However, none of these studies compared instantaneous GPS speed nor change in speed to a criterion value.

Laser measurement devices produce valid and reliable estimates of distance from which speed data can be derived (Harrison, Jensen, & Donoghue, 2005). Compared to timing gates which can only determine average speed based on a limited number of samples, laser devices sample at 50^{+} Hz allowing the collection of practically instantaneous speed data. This allows a more

sensitive measure of the changes in speed during rapid actions, such as acceleration and decelerations. Therefore, the laser should provide more reliable and valid measures than timing gates.

Consequently, the aims of this study were to determine the validity and reliability of 5 and 10 Hz GPS for measuring instantaneous speed during the acceleration, deceleration and constant speed phase of straight-line running.

3.2 Methods

Three sub-elite team sport athletes (age: 27 ± 3 yrs) volunteered and provided written consent to participate in this study. As the primary measure of this study was the raw GPS data the number of participants does not reflect the sample size as it is the number of samples collected and trials undertaken which is of most importance. The study was approved by the Victoria University Human Research Ethics Committee and conformed to the Declaration of Helsinki.

The study determined the validity and reliability of 5 and 10 Hz GPS for measuring changes in speed. Participants were asked to perform straight-line running along a marked line. Each trial required the participant to establish and maintain a constant running speed before performing an acceleration effort and finally decelerating to a complete stop. A total of 80 straight-line running trials were undertaken.

Running speed was recorded using a Laveg laser (LAVEG Sport, Jenoptik, Jena, Germany) sampling at 50 Hz, which was the criterion measure during all testing. The error of the laser for determining distance travelled has been identified as 0.10 ± 0.06 m over 100 m (Arsac & Locatelli, 2002) with a CV of up to 0.2% over 10, 30, 50 and 70m (Harrison, Jensen, & Donoghue, 2005). Similarly, the laser has a reported average speed error of < 2% (Turk-Noack & Schmalz, 1994). Reliability of the laser for measuring speed has been assessed through repeated running trials giving a TE of 0.05 $m.s^{-1}$ and a high interclass correlation (r = 0.98) (Duthie, et al., 2006). The laser was positioned on a tripod 2 m behind the starting point and aligned with the centre of the participants back to ensure they stayed in focus for the full

duration of each trial. Additionally participants wore a white shirt during all testing as this offered an appropriate reflective surface for the laser signal.

During each trial the participants wore two 5 Hz or two 10 Hz GPS units (MinimaxX, V2.0 and V4.0 respectively, Catapult Innovations, Scoresby, Australia) positioned approximately 25 cm apart on the upper back in a custom-made vest. The antennas of each unit were exposed to allow clear satellite reception (Jennings, et al., 2010a). Participants were asked to produce an acceleration effort from a range of starting speeds common in team sport (1 – 6 $m.s^{-1}$).

Participants were provided with instant feedback on their running speed during each trial. A computer was connected to the laser and using custom software, instantaneous speed data was obtained during each trial. The speed bands for the desired constant speed were entered into the software and feedback transmitted via a 2-way radio device (TX670 UHF Handheld Transceiver, GME, Sydney, Australia). Participants were given a radio device to hold throughout each trial which provided feedback through several audio cues. Participants heard a low pitch if their commencement speed prior to acceleration was too low, a high pitch if too fast, silence if they were within the required speed threshold and an alternating pitch once the appropriate constant speed had been maintained for a minimum of two seconds. Participants were informed to accelerate maximally for several seconds upon hearing the alternating pitch before decelerating to a complete stop to conclude the trial.

The mean ± standard deviation (SD) number of satellites during data collection was 12 ± 1.5. The horizontal dilution of position (HDOP) is an indication of the accuracy of the GPS horizontal positional signal determined by the geographical organisation of satellites. Values range from 1 to 50, with 1 indicative of an ideal positional fix and increasing values signifying positional unreliability (Witte & Wilson, 2004). The mean ± SD HDOP during data collection was 0.9 ± 0.2.

Laser speed data was re-sampled to 5 Hz and 10 Hz for comparison to respective GPS devices and synchronised at the first movement recorded above zero $m.s^{-1}$ to account for processing phase delays inherent with these GPS systems. The re-sampling technique involved taking a

sample from the laser data corresponding to the equivalent sample at the slower frequency. For example when re-sampling to 10 Hz every fifth sample was taken from the 50 Hz data. This was deemed to be the best method to simulate a true reflection of the slower sampling frequency. Raw laser data was clipped above 12 and below -1 $m.s^{-1}$ respectively to account for errors where the participant may have moved outside the sight of the laser. Trials were divided into three phases; constant speed, acceleration and deceleration. Constant speed was categorised as 1 – 3, 3 – 5 and 5 – 8 $m.s^{-1}$, acceleration as commencing from 1 – 3, 3 – 5 and 5 – 8 $m.s^{-1}$ and deceleration as commencing from 5 – 8 $m.s^{-1}$.

All data was log-transformed to reduce bias due to non-uniformity of error. Validity was calculated by SEE and expressed as a standard deviation (± 90% confidence limits) of the percentage difference between criterion speed (laser) and GPS speed. Further, bias was reported as the percentage difference between the reference speed and GPS speed. Finally a Pearson product-moment correlation between criterion and GPS speed was calculated.

Inter-unit reliability (10 Hz-10 Hz), (5 Hz-5 Hz) were assessed and expressed as typical error and a coefficient of variation (± 90% confidence limits). The utility of the devices for use in team sports were assessed by comparing the calculated smallest worthwhile change (0.2 × between-subject standard deviation (Batterham & Hopkins, 2006)) to the coefficient of variation.

3.3 Results

Higher commencement speeds improved the measurement accuracy for detecting accelerations with both 5 and 10 Hz GPS (Table 3-1). Similarly, validity improved during higher constant speeds and with an increased sampling rate for measuring constant speed, acceleration and deceleration (Table 3-1).

Both 5 and 10 Hz GPS underestimated the criterion speed during the acceleration phase (Table 3-1). Constant speed was underestimated at 5 – 8 $m.s^{-1}$ for 5 Hz and 3 – 5 and 5 – 8 $m.s^{-1}$ for 10 Hz. Conversely, constant speed was overestimated at 1 – 3 and 3 – 5 $m.s^{-1}$ for 5 Hz and 1 – 3 $m.s^{-1}$ for 10 Hz. Lower errors were associated with constant speed running

(Table 3-1). Instantaneous speed was overestimated during the deceleration phase. The magnitude of the error was reduced with an increased sampling frequency across all phases.

The criterion and GPS speeds were strongly correlated for all phases when sampling at a higher rate (Table 3-1). Weaker correlations were associated with higher constant and commencement speeds during all phases in 5 Hz GPS units.

Reliability improved at higher commencement speeds during both the constant speed and acceleration phases irrespective of sampling rate (Table 3-2). A higher sampling rate did, however, demonstrate an improved level of reliability during the constant speed and acceleration phase and deceleration phase (coefficient of variation < 5.3% and < 6% respectively, Table 3-2), compared to a lower sampling rate (Table 3-2).

GPS sampling at 5 Hz was incapable of detecting the smallest worthwhile change during all phases of these tests (coefficient of variation > smallest worthwhile change, Table 3-2). In contrast 10 Hz GPS was able to detect the smallest worthwhile change during the constant speed and acceleration phase for 1 – 3 $m.s^{-1}$ and during the deceleration phase. Similarly 10 Hz GPS was acceptable for detecting the smallest worthwhile change during the constant speed and acceleration phase for 3 – 5 and 5 – 8 $m.s^{-1}$ (Similar coefficient of variation and smallest worthwhile change values, Table 3-2).

Table 3-1 Validity of 5 and 10 Hz GPS devices for measuring instantaneous speed

	Starting Speed ($m.s^{-1}$)	CV as %		Bias as %		Pearson Correlation		No of Trials		No of Samples		Mean Time (s)		Mean Distance (m)	
		5 Hz	10 Hz	5 Hz	10 Hz	5 Hz	10 Hz	5 Hz	10 Hz	5 Hz	10 Hz	5 Hz	10 Hz	5 Hz	10 Hz
Constant Speed	1-3	11.1 ± 0.58	8.3 ± 0.27	2.4 ± 0.8	0.6 ± 0.4	0.91 ± 0.01	0.96 ± 0.00	26	43	561	1348	4.01	3.15	8.0	6.5
	3-5	10.6 ± 0.59	4.3 ± 0.15	0.3 ± 0.8	-0.2 ± 0.2	0.77 ± 0.03	0.95 ± 0.00	22	45	485	1119	3.34	2.53	13.5	10.6
	5-8	3.6 ± 0.26	3.1 ± 0.13	-0.5 ± 0.8	-0.2 ± 0.2	0.28 ± 0.09	0.92 ± 0.01	11	34	266	755	3.33	2.24	18.2	12.9
Acceleration	1-3	14.9 ± 1.16	5.9 ± 0.23	-9.6 ± 1.3	-2.9 ± 0.3	0.9 ± 0.02	0.98 ± 0.00	26	45	259	929	1.84	2.17	8.8	11.4
	3-5	9.5 ± 0.79	4.9 ± 0.21	-5.0 ± 1.0	-3.6 ± 0.3	0.82 ± 0.04	0.98 ± 0.00	22	43	220	772	1.52	1.70	8.4	10.3
	5-8	7.1 ± 0.87	3.6 ± 0.18	-5.2 ± 1.4	-2.1 ± 0.2	0.5 ± 0.12	0.92 ± 0.01	11	36	103	537	1.29	1.57	8.2	10.9
Deceleration	5-8	33.2 ± 1.64	11.3 ± 0.44	19.3 ± 2.1	8.9 ± 0.8	0.83 ± 0.02	0.98 ± 0.00	59	46	735	986	2.07	2.70	8.55	12.0

All data is comparison of GPS data to criterion values obtained from instantaneous speed recorded by laser. Data is expressed as a coefficient of variation (CV), percent bias and a correlation statistic

Table 3-2 Reliability of 5 and 10 Hz GPS devices for measuring instantaneous speed

	Starting Speed	TE ($m.s^{-1}$)		SWC as %		CV as %		Pearson Correlation		No of Trials		No of Samples		Mean Time (s)		Mean Distance (m)	
	($m.s^{-1}$)	5 Hz	10 Hz	5 Hz	10 Hz	5 Hz	10 Hz	5 Hz	10 Hz	5 Hz	10 Hz	5 Hz	10 Hz	5 Hz	10 Hz	5 Hz	10 Hz
Constant Speed	1-3	0.21 ± 0.02	0.12 ± 0.00	5.91	6.66	12.4 ± 1.18	5.3 ± 0.22	0.80 ± 0.05	0.97 ± 0.00	10	20	171	837	3.91	3.09	7.6	6.3
	3-5	0.27 ± 0.03	0.13 ± 0.01	3.38	2.85	6.7 ± 0.68	3.5 ± 0.20	0.83 ± 0.04	0.94 ± 0.01	10	19	145	448	3.77	2.46	14.9	10.3
	5-8	0.35 ± 0.05	0.11 ± 0.01	1.43	1.92	6.3 ± 0.83	2.0 ± 0.12	0.22 ± 0.18	0.96 ± 0.01	5	15	80	365	3.76	2.19	20.5	12.6
Acceleration	1-3	0.50 ± 0.06	0.18 ± 0.01	9.07	8.21	16.2 ± 1.99	4.3 ± 0.24	0.84 ± 0.05	0.98 ± 0.00	10	20	108	486	1.67	2.13	7.8	11.3
	3-5	0.43 ± 0.05	0.20 ± 0.01	3.64	3.64	9.5 ± 1.18	4.2 ± 0.26	0.74 ± 0.08	0.94 ± 0.01	10	19	100	364	1.32	1.68	7.2	10.1
	5-8	0.60 ± 0.12	0.13 ± 0.01	2.20	1.86	11.0 ± 2.29	1.9 ± 0.15	0.00 ± 0.27	0.95 ± 0.01	5	15	39	240	1.20	1.64	7.9	11.5
Deceleration	5-8	0.83 ± 0.07	0.16 ± 0.01	12.46	14.99	31.8 ± 2.99	6.0 ± 0.33	0.69 ± 0.06	0.99 ± 0.00	25	17	206	475	2.01	2.80	8.2	12.5

All data is comparison of one GPS device to a second device located on each participant during each trial. Data is expressed as a typical error (TE) and as a coefficient of variation (CV). The smallest worthwhile change (SWC) was calculated as 0.2 × between-subject SD (Batterham & Hopkins, 2006)

3.4 Discussion

This study was the first to determine the validity and reliability of 5 and 10 Hz GPS units for measuring instantaneous changes in speed. The major finding was that the V4.0 MinimaxX were 2 – 3 times more accurate than V2.0 units at detecting change in speed and up to 6-fold more reliable. These newer devices provided an acceptable level of accuracy and reliability for determining instantaneous speed for all phases of straight line running.

During the constant speed and acceleration phases, GPS accuracy increased at higher constant and commencement speeds by up to 67 and 52% respectively, when compared to those at lower speeds. In contrast, the accuracy of GPS for measuring distance has been reported to decrease at higher running speeds (Jennings, et al., 2010a; Petersen, et al., 2009). However in those studies, trials were not separated into running phases therefore high-speed trials contained large changes of speed, as they were undertaken from low starting speeds (Jennings, et al., 2010a; Petersen, et al., 2009). In this study, the increase in accuracy reported may be attributed to less variation in the change of speed when commencing from 5 – 8 $m.s^{-1}$ as participants only achieved a maximal speed of ~7.5 $m.s^{-1}$. Incidentally, similar top speeds have been reported in team-sport athletes including elite soccer and Australian footballers (~7.6 and ~8.6 $m.s^{-1}$, respectively) (Bradley, et al., 2009b; Young, et al., 2008). Therefore, the methods in this study, used to assess GPS speed measurements had an acceptable ecological validity as the range of speeds undertaken by participants were representative of what is performed by team-sports athletes.

The underestimation of true speed during phases involving high-speed movement was similar to 1 Hz GPS compared to speedometer speed during track cycling (Witte & Wilson, 2004). The greatest over- and under-estimations of true speed occurred with the older V2.0 MinimaxX units. Similarly, greater errors for measuring distance have been reported in 1 Hz compared to 5 Hz GPS units indicating that it may be sample rate that limits the accurate detection of both distance and speed (Jennings, et al., 2010a). This is supported by the validation of 10 Hz units for measuring sprint distance over 15 and 30 m with an improved coefficient of variation of < 4% (Castellano, et al., 2011). With the exception of low starting

speed accelerations (5 Hz) and decelerations (5 and 10 Hz), all speed measures were less than 5% from criterion values. The magnitude of these errors may not be large enough to significantly affect the classification of movements when analysing the movement demands of team-sports athletes, due to the inherent variability of match running performance. Only one study has determined the coefficient of variation of running in team sport from match-to-match using 5 Hz GPS. Both total and high-speed running distance had a coefficient of variation of ~10% and the number of maximal accelerations ~51% (Aughey, 2011b). The coefficient of variation for both V2.0 and 4.0 MinimaxX for measuring constant speed was either below or close to these values for match running while the coefficient of variation for measuring acceleration was substantially lower than the variation in acceleration efforts. Therefore, researchers can confidentially use these units to detect changes in match running during team-sports as the signal is greater than the inherent noise. Although there were differences in the mean duration and distance over which accelerations occurred in the 5 and 10 Hz trials, the greatest discrepancy was 0.45 s (2 and 4 samples from each unit respectively). Given this small difference in samples, comparison between the 5 and 10 Hz units should not be unduly affected.

The strong validity and reliability correlations when comparing V4.0 MinimaxX speed to the criterion suggest that although there is a degree of error when measuring instantaneous speed, 10 Hz GPS can at least accurately determine that an acceleration or deceleration effort has occurred. This has implications for the analysis of team-sport, as researchers can determine the number of acceleration or decelerations efforts undertaken by athletes over the course of a match. Caution should be exercised when using V2.0 MinimaxX for measuring instantaneous speed due to the weak correlation with the criterion measure. However, team-sport data can still be analysed by accounting for match running variability.

The accuracy of GPS in measuring changes in speed during deceleration was poor with overestimations of up to 19.3%. In this study deceleration efforts contained the greatest rate of change in speed, on average 17.4% greater than during acceleration efforts. As is evidenced by similar high coefficient of variations in accelerations commencing from 1 – 3 $m.s^{-1}$, GPS

accuracy is negatively affected by a high rate of change in speed. Although an increased sampling rate improved accuracy, researchers may be limited to simply reporting the occurrence of deceleration efforts, as opposed to quantifying their magnitude in terms of distance and duration.

The inter-unit reliability was superior in the more modern devices tested here. Importantly 10 Hz GPS had a coefficient of variation less than or similar to the calculated smallest worthwhile change during all phases. Therefore V4.0 MinimaxX may provide a sufficient sensitivity for detecting small and important changes in performance of acceleration, deceleration and constant speed movements common in team sport. However future match analysis research should quantify the match-to-match variability in team-sport running to support the ecological validity of these devices. While unable to detect the smallest worthwhile change in the tests employed in this study, 5 Hz GPS can be used to quantify team-sport running as the coefficient of variation is less than or approximately the reported match-to-match running variability (Aughey, 2011b). To remove as much associated error as possible, researchers should use the same devices on the same individuals when monitoring team-sports athletes.

This study was limited in its specificity to team-sport movement demands as athletes often change direction, whereas only straight-line running was reported. Future research should investigate the validity and reliability of GPS technology for measuring changes in speed during non-linear movements.

3.5 Conclusions

The data presented details the superior validity and inter-unit reliability of V4.0 MinimaxX compared to the older V2.0 units. While these improvements appear to be linked to the higher sampling frequency, the manufacturers claim that the advanced chipsets used with the latest models, may be largely responsible. The latest V4.0 units sampling at 10 Hz produce sufficient accuracy to quantify the acceleration, deceleration and constant speed running phases in team sports.

CHAPTER 4. STUDY 2: ACCELERATION PROFILES IN ELITE AUSTRALIAN SOCCER

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4.1 Introduction

The analysis of in-game movement profiles of team-sport athletes has been of interest to researchers and sport science practitioners since the early 1970's (Brooke & Knowles, 1974). This physical profiling has described soccer as a predominantly aerobic sport, interspersed with frequent bouts of high-speed movements (Bangsbo, 1994). Most soccer research has focussed on quantifying and subsequently training the capacity to perform high speed movements (Bradley, et al., 2009b; Di Salvo, et al., 2009; Impellizzeri, et al., 2006). This interest can be attributed to the idea that these movements impose a physical strain upon the athlete and should be developed through specific conditioning (Iaia, Rampinini, & Bangsbo, 2009).

High-speed running distance has been suggested to be a valid measure of physical performance as it is associated with a higher standard of play with elite level players covering a 28% greater in-game distance at high-speed running than their moderate level counterparts (Mohr, Krustrup, & Bangsbo, 2003). However, at the same level of competition less successful teams cover a greater high-speed running distance than more successful teams (Rampinini, et al., 2009a). Further, a given team will perform more high-speed running against the better teams in the competition and less against the worst (Rampinini, et al., 2007b). The ability for a player to undertake sprint efforts (short movements occurring close to maximal running speed) have also been identified as being important (Di Salvo, et al., 2010) for critical match activities, such as being first to the ball, moving past an opponent and creating or stopping goal scoring opportunities (Reilly, Bangsbo, & Franks, 2000).

Acceleration, defined as the rate of change in speed (Little & Williams, 2005), is a physically demanding task (Cavagna, Komarek, & Mazzoleni, 1971). To accelerate is more energetically demanding than constant-speed movement (Osgnach, et al., 2010). During a maximal 5 s sprint, not only is 50% of the total work achieved within the first 1.5 s (Cavagna, Komarek, & Mazzoleni, 1971), but a peak power output ($W.kg^{-1}$) 40% greater than the average power output is obtained after only ~0.5 s (di Prampero, et al., 2005). The power output required to run at a high-speed (~4.17 $m.s^{-1}$) is 54% greater than that required to run at a low-speed (2.5 $m.s^{-1}$) (Osgnach, et al., 2010). However, performing an acceleration from the lower speed can match or even exceed the power output required to maintain the higher speed (Osgnach, et al., 2010). Therefore, accelerating is not only a metabolically demanding task, but one that does not need to occur at a high speed to be physically challenging.

The relationship between an athlete's capacity to accelerate and maximal running speed has been investigated predominantly via field-based testing. Player performance in a 10 m sprint and 20 m flying sprint test, to assess acceleration and maximal speed respectively had large correlations in adults (Pearson's r = 0.62 (Little & Williams, 2005)), and in under 14 to 18 year olds (r = 0.56 – 0.79 (Mendez-Villanueva, et al., 2011a)). However, the in-game relationship between an athlete's acceleration performance and attainment of maximal running speed may differ markedly from test-based findings. Given the required distance to achieve maximal speed from a standing or running start (~40 m and ~29 m (Benton, 2000) respectively) and the short sprint distances (< 10 m (Di Salvo, et al., 2010; Di Salvo, et al., 2009)) associated with soccer, the capacity to accelerate could be of greater value in determining the outcome of decisive match activities. Indeed, elite players in the English Premier League preceded a sprint effort with a fast acceleration for only 30% of all sprints, however no information was provided on the total number of accelerations undertaken (Di Salvo, et al., 2009). The activity profiles in soccer are position specific, due to a players tactical role and available space on the pitch (Bradley, et al., 2009b; Di Salvo, et al., 2010), however it is unclear whether positional differences exist in acceleration profiles and the interaction between accelerations and high-speed movements.

High-intensity movements have typically been recorded as only occurring at high running speeds (Bradley, et al., 2009b; Di Salvo, et al., 2009; Rampinini, et al., 2007b). The estimation of an athlete's energy cost and metabolic power output when accelerating during a soccer match suggest that a maximal acceleration commencing from a low speed is a high-intensity task (Osgnach, et al., 2010) but would not be considered under previous classifications. Motion analysis that excludes accelerations probably underestimates high-intensity power output as players must accelerate frequently (Bradley, et al., 2009a). This presents an argument that the study of acceleration in conjunction with high-speed running, as markers of high-intensity activity, may be of greater value in understanding the high-intensity movement profiles of athletes during competition.

Therefore the aim of this research was to investigate the acceleration and high-speed movement profiles of elite soccer players competing in the domestic Australian league.

4.2 Methods

Twenty-nine elite male soccer players registered to two teams playing in the Australian A-League provided informed consent to participate in the study which was approved by the Victoria University Human Research Ethics Committee and was performed in accordance with the ethical standards of the International Journal of Sports Medicine (Harriss & Atkinson, 2011). Player speed data was measured via global positioning system (GPS) units sampling at 5 Hz (SPI-Pro, GPSports, Australia) from outfield players between 1 and 11 occasions during the 2010-2011 competitive season (34 matches, 126 individual match files). Only files from players who completed the full match were included. The average number of available satellite signals during matches was 8 ± 1.

Player movement categories were defined according to commonly used speed thresholds: high-speed running (HiSR, ≥ 4.17 m.s^{-1}), sprinting (6.94 - 10.00 m.s^{-1}) (Bradley, et al., 2009b; Di Salvo, et al., 2009; Rampinini, et al., 2007b) and maximal acceleration (> 2.78 m.s^{-2}) (Aughey, 2010, 2011b; Gabbett, Jenkins, & Abernethy, 2012). As a maximal acceleration may overlap with high-speed running, when occurring concomitantly these two efforts were combined to form high-intensity activity (HIA). This term was used as a comprehensive quantification of the occurrence of a physically demanding effort. Finally, to determine the number of maximal accelerations that did not exceed 4.17 m.s^{-1} the number of HiSR efforts were subtracted from the number of HIA efforts, this was termed low-speed acceleration (LSA). Raw GPS distance and speed data was analysed using a custom excel spreadsheet. Speed was calculated using the Doppler shift method, as opposed to the differentiation of positional data, as it is associated with a higher level of precision (Townshend, Worringham, & Stewart, 2008).

The number of HiSR, sprint, maximal acceleration, HIA and LSA efforts were determined and expressed per half and as a total match. The commencement speed of maximal acceleration efforts were calculated in 1 m.s^{-1} speed bands, ranging from 1 to > 4 m.s^{-1} and expressed as a percentage of total maximal accelerations for the match. Following commencement of a maximal acceleration a player may continue to accelerate at a

submaximal rate after dropping below the maximal acceleration threshold (2.78 $m.s^{-2}$), therefore the final speed following a maximal acceleration was determined for each effort in two different ways; i) when the rate of acceleration dropped below 2.78 $m.s^{-2}$ (Figure 4-1 panel a); and ii) when the rate of acceleration dropped below 0 $m.s^{-2}$ (Figure 4-1 panel b). Due to the large range of values (1 - 8 $m.s^{-1}$), final speeds were grouped into the categories: walk (0 - 2.1 $m.s^{-1}$), jog (2.2 - 4.16 $m.s^{-1}$), HiSR (4.17 - 6.93 $m.s^{-1}$) and sprint (≥ 6.94 $m.s^{-1}$). Finally to explore the maximal acceleration/sprint relationship the method used by Di Salvo (Di Salvo, et al., 2010; Di Salvo, et al., 2009) was adapted and divided sprints into i) those where the preceding acceleration was maximal and ii) those where the preceding acceleration was not maximal.

In study one of this thesis the ability of 5 Hz MinimaxX GPS (V2.0) to measure instantaneous changes of speed when accelerating was assessed and a percentage bias between -5 to -9.6% was found when compared against a laser as the criterion measure, and a typical error expressed as a coefficient of variation between 7.1 and 14.9% (Table 3-1). Similarly, the reliability for assessing these movements when expressed as a coefficient of variation was between 9.5 to 16.2% (Table 3-2). Although the brand of GPS used in this study has not been validated for assessing instantaneous changes in speed, the assessment of both 5 Hz MinimaxX (V2.0) and GPSports (SPI-Pro) units for measuring distance during sprints found the GPSports units to have a smaller standard error of the estimate, percentage bias and better reliability than MinimaxX (Petersen, et al., 2009). While speed was not measured, the sprints were conducted from a standing start, suggesting the GPSports units have an improved validity and reliability when assessing rapid changes in speed compared to MinimaxX. To enhance the ecological validity and reliability of this measure a minimum of two consecutive samples (0.4 s) above the designated speed threshold was required for an effort to be considered real and not a product of the inherent noise associated with 5 Hz GPS (Aughey, 2011b). Finally as the results of study one suggest that 5 Hz GPS underestimates instantaneous speed during acceleration and high-speed movements any reported values in this study are the minimum of what a player would actually undertake during a match.

To identify acceleration and high-speed movement characteristics related to playing position, match incidences were grouped into one of five positions: central defenders (n = 5 players, 31 files), wide defenders (n = 3, 17 files), central midfielders (n = 7 players, 33 files), wide players (n = 6 players, 25 files) and forwards (n = 8 players, 20 files).

Data are expressed as mean ± SD. All data was tested for normality using the Kolmogorov-Smirnov normality test and a Levene test to verify homogeneity of variance. For data that was not normally distributed non-parametric tests were used. A Kruskal-Wallis' test detected main differences between positions, halves and the percentage distribution of maximal accelerations based on commencement and final speeds, with a Mann-Whitney and Wilcoxon post-hoc tests to determine specific differences respectively. All other data was analysed using a one-way ANOVA with Bonferroni post-hoc tests to determine specific differences between positions. A one-way repeated measures ANOVA was used to identify differences between each half with paired t-tests to determine statistical significance.

4.3 Results

The number of efforts (mean ± SD) undertaken by players in each movement category for each position per half of the match is in Table 4.1.

Table 4-1 Number of efforts for high-intensity movements in the 1st and 2nd half and as a match total according to playing positions

Match Activity	Half	Central Defender	Wide Defender	Central Midfielder	Wide Midfielder	Forward
High-speed running	1st half	53 ± 15 [a, c]	81 ± 10 [b]	63 ± 25	76 ± 17	66 ± 20
	2nd half	52 ± 16 [a]	76 ± 16	62 ± 20	65 ± 17 *	60 ± 13
	Total	104 ± 28 [a, c]	156 ± 22 [b]	125 ± 41	141 ± 31 [d]	127 ± 23
Sprinting	1st half	2 ± 2 [a, c, d]	7 ± 3 [b, c]	2 ± 2 [c, d]	5 ± 3 [d]	7 ± 4
	2nd half	3 ± 2 [a, d]	5 ± 3 [b, c]	2 ± 2 [d]	3 ± 2 *, [d]	7± 4
	Total	5 ± 3 [a, c, d]	12 ± 5 [b, c]	4 ± 4 [c, d]	8 ± 4 [d]	14 ± 6
Maximal acceleration	1st half	28 ± 10 [a]	47 ± 7 [b, c, d]	30 ± 13	35 ± 10	34 ± 12
	2nd half	28 ± 11 [a]	43 ± 10 [b, c,]	30 ± 10	30 ± 11 *	34 ± 10
	Total	56 ± 18 [a]	90 ± 15 [b, c, d]	60 ± 20	65 ± 18	69 ± 19
High-intensity activity	1st half	74 ± 21 [a, c]	114 ± 10 [b, d]	84 ± 32	100 ± 22	90 ± 27
	2nd half	71 ± 21 [a]	106 ± 21 [b, c, d]	83 ± 24	86 ± 23 *	84 ± 24
	Total	145 ± 38 [a, c]	220 ± 29 [b, d]	167 ± 51	186 ± 41	173 ± 33
Low-speed acceleration	1st half	21 ± 7 [a]	33 ± 7 [b, c, d]	21 ± 10	24 ± 8	22 ± 9
	2nd half	19 ± 8 [a]	31 ± 9 [b, c]	21 ± 8	21 ± 9	24 ± 8
	Total	40 ± 14 [a]	64 ± 13 [b, c, d]	42 ± 14	45 ± 14	46 ± 15

All data is mean ± SD. a: significant difference vs. wide defender ($P < 0.05$), b: vs. central midfielder, c: vs. wide midfielder, d: vs. forward, *vs. 1st half

The commencement and final speeds of maximal accelerations are represented in Figure 4-1. Of total maximal acceleration, 48% were undertaken from a starting speed < 1 $m.s^{-1}$, with a further 30% commencing from 1-2 $m.s^{-1}$, 14% from 2-3 $m.s^{-1}$, 6% from 3-4 $m.s^{-1}$ and 2% from > 4 $m.s^{-1}$ (Figure 4-1). The percentage of maximal acceleration from each starting speed was significantly different from all others ($P < 0.01$). Following commencement of a maximal acceleration less than 1% of efforts reached the sprint speed threshold while still accelerating at a maximal rate (≥ 2.78 $m.s^{-2}$) (Figure 4-1 panel a), and only 4% of efforts when the player continued to accelerate after dropping below the maximal acceleration threshold (Figure 4-1 panel b).

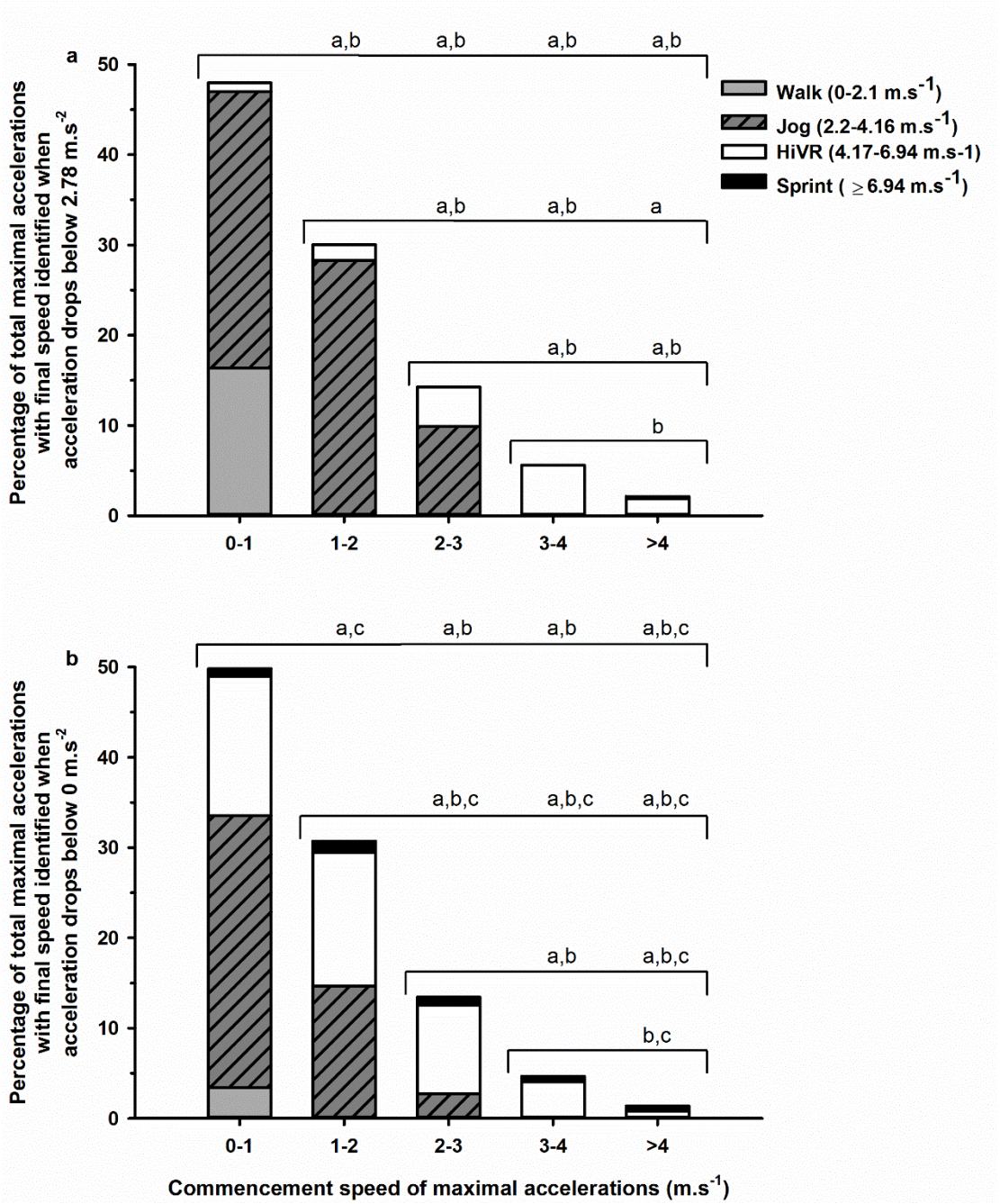

Figure 4-1 Percentage distribution of total maximal accelerations based on final speed (Walk, Jog, HiSR and Sprint) when acceleration drops below 2.78 m.s^{-2} panel a), and when acceleration drops below 0 m.s^{-2} panel b) as a function of starting speed. a: significant difference in percentage of maximal accelerations where final speed = jog ($P < 0.05$), b: final speed = HiSR, c: final speed = sprint. HiSR = High-speed running

There were no differences in the commencement and final speeds of maximal accelerations between playing positions. The percentage of total sprints preceded by either a maximal acceleration or submaximal acceleration for each position is shown in Figure 4-2. The

relationship between the number of total match high-speed running and sprint efforts to maximal accelerations for each position is shown in Figure 4-3 (mean ± SD). There was no difference between central defenders and central midfielders in the number of efforts performed across all movements ($P > 0.084$). Wide defenders performed the greatest number of maximal accelerations and low speed accelerations across all playing periods ($P < 0.006$ and $P < 0.001$ respectively). Central defenders and midfielders performed the least number of sprints ($P < 0.02$) while wide defenders and forwards performed the most ($P < 0.001$). There were no differences in the number of high-intensity activities performed by central defenders, midfielders and forwards ($P > 0.176$). Although wide defenders performed significantly more high-intensity activities than these positions ($P < 0.006$), there was no differences between the number of these efforts performed by wide defenders and wide midfielders ($P > 0.078$). There were no differences in the number of efforts across all movements in the 2nd half compared to the 1st with the exception of wide midefielders who performed fewer high-speed running ($P < 0.001$), sprint ($P = 0.029$), maximal acceleration ($P = 0.029$) and high-intensity activity efforts ($P = 0.001$). A full summary of the positional differences is presented in

Table 4-1.

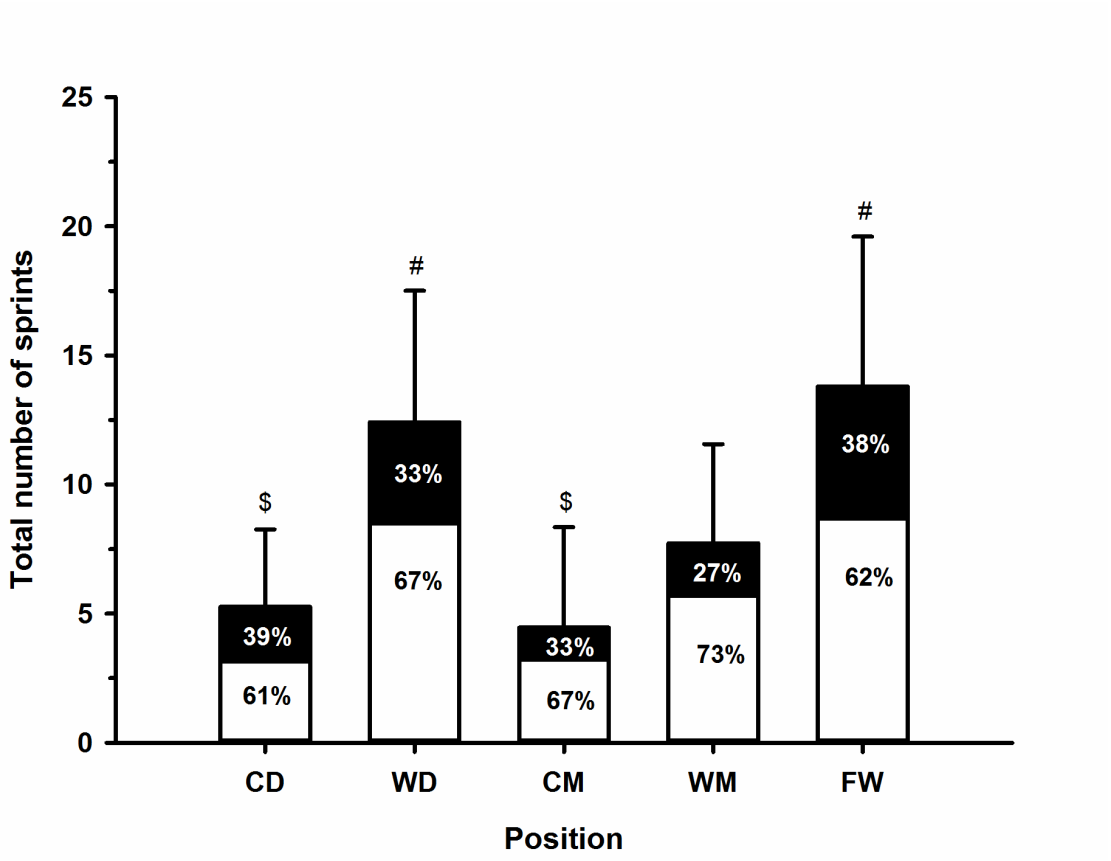

Figure 4-2 Ratio of sprints preceded by maximal (black fill) or submaximal (white fill) accelerations as a function of playing position. Total number of sprints differ between all positions ($P < 0.05$) with the exception of $ central defenders vs central midfielders and # wide defenders vs forwards. CD = central defender, WD = wide defender, CM = central midfielder, WM = wide midfielder, FW = forward

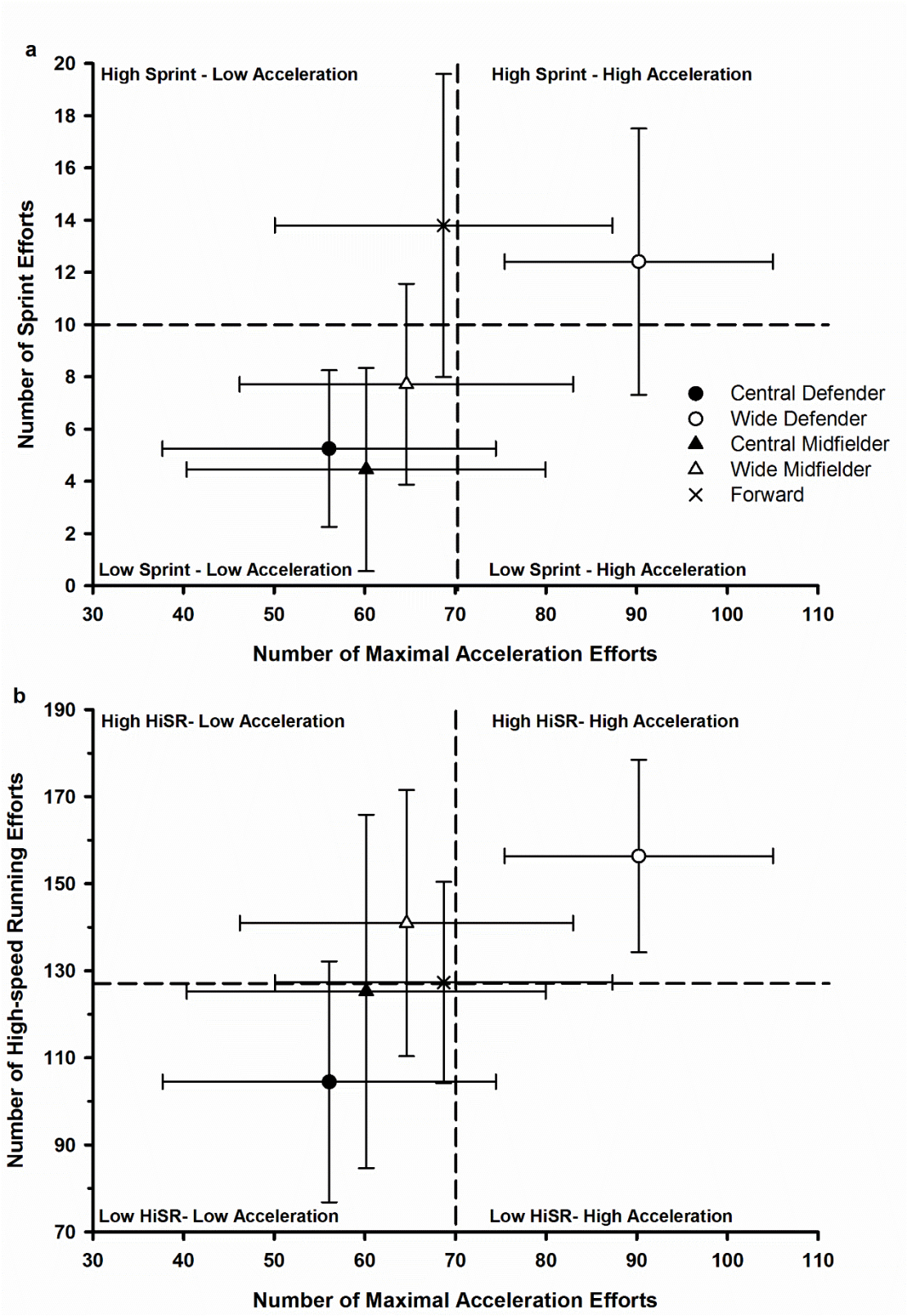

Figure 4-3 Positional differences for the number of maximal acceleration and sprint efforts panel a) and high-speed running efforts panel b) undertaken per match (mean ± SD). Data is divided into high and low categories based upon the average number of efforts per match reported in Table 4-1

4.4 Discussion

The research presented in this study characterises the acceleration profiles of elite soccer players and for the first time identifies differences between acceleration and high-speed efforts. Players performed frequent high-speed running efforts during match-play but ~8-fold greater maximal accelerations than sprints.

Due to differences in the movement definitions and analysis techniques used, the interpretation and comparison of this research with others is difficult and should be done with caution. On average elite players in the English premier league, as quantified using a semi-automated tracking system (Prozone^{TM}), performed ~3 fold more acceleration (> 2.5 m.s^{-2}) than sprint (> 5.5 m.s^{-1}) efforts a game (119 and 36 efforts respectively) (Bradley, et al., 2009a). The simultaneous use of 5 Hz GPS and Prozone^{TM} to measure in-game high-speed and sprint running distance shows GPS reports significantly lower values (223 vs. 246 m and 20 vs. 34 m, respectively) (Harley et al., 2011), however there has yet to be a comparison between these system's ability to detect effort occurrence for high-intensity movements. The systemic underestimation of instantaneous speed when using 5 Hz GPS (See Chapter 3) may explain the lower number of efforts reported in this study, as Australian players seem to perform a similar number of sprint efforts to overseas players when assessed with a video based tracking system (Burgess, Naughton, & Norton, 2006). Tracked with a semi-automated system, elite players in the Italian league accelerated maximally (> 3m.s^{-2}) for a total distance of 180 m and duration of 51 s (Osgnach, et al., 2010). Although these values are low, a theoretical model was used to estimate a corresponding energy cost to maximally accelerate of > 17.28 J.kg^{-1}.min^{-1} suggesting maximal accelerations to be a highly demanding task. This research explores another aspect of maximal accelerations by detailing associated running speeds and position specific differences.

The majority of match analysis research has only quantified high-intensity movements as occurring at high speeds (Bradley, et al., 2009b; Di Salvo, et al., 2010; Di Salvo, et al., 2009). In this study, players predominantly accelerated from a standing start with 98% of maximal accelerations commenced from a speed < 4 m.s^{-1} (Figure 4-1 panel a). Furthermore, 85% of

maximal accelerations had a final speed < 4.17 m.s^{-1} (Figure 4-1 panel a). It could be argued that following a maximal acceleration a player will often continue to accelerate, albeit at a submaximal rate, leading into a high-speed effort. However, based on the research presented in this study only ~49% of maximal accelerations led into a speed ≥ 4.17 m.s^{-1} (Figure 4-1 panel b). Sprint efforts have been categorised based on the type of preceding acceleration with an explosive sprint defined as attainment of sprint speed (> 7 m.s^{-1}) with time spent in the previous speed category (5.5 to 7 m.s^{-1}) being less than 0.5 s (Di Salvo, et al., 2010; Di Salvo, et al., 2009). Given this definition, the minimum rate of acceleration prior to an explosive sprint can be calculated to be 3 m.s^{-2}. Of the total sprints performed per match by players competing in the English Premier League only 30% were explosive sprints, inferring the remaining 70% to be preceded by a submaximal acceleration. The data in this study supports this with only 34% of sprint efforts preceded by a maximal acceleration (

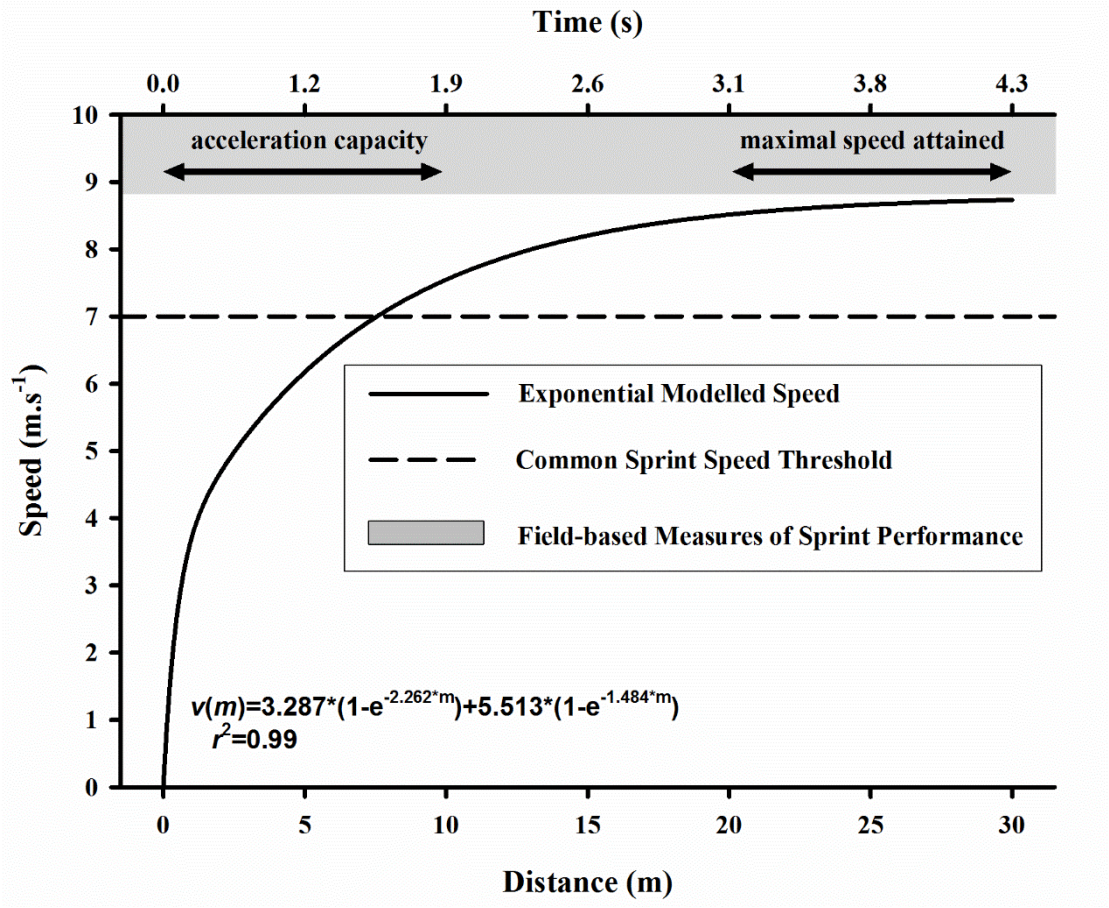

Figure 2-1). This suggests that despite the large correlations between acceleration and maximal speed in field-based testing, during match-play a player is not always required to

maximally accelerate to achieve maximal speed and that performing a maximal acceleration will not always lead to maximal or high-speed running.

The majority of accelerations undertaken by Australian soccer players would not be included if high-intensity activity was quantified purely as a measure of high-speed running. Given the high metabolic cost required to accelerate (Osgnach, et al., 2010), and that the number of accelerations reported in this study are most likely the minimum of what are actually performed, it is likely that the exclusion of accelerations in match analysis research results in an underestimation of high-intensity movements.

The results of this study identify that different high-speed movement and acceleration profiles exist between positions (Table 4-1 and Figure 4-3). It is common for central defenders and central midfielders to perform fewer sprints than other positions (Bradley, et al., 2009b; Di Salvo, et al., 2010; Di Salvo, et al., 2009; Hopkins et al., 2009), possibly due to a lack of space available to these roles, leaving an insufficient distance for sprinting speed to be attained. The defensive roles of these central positions may also limit the amount of sprints undertaken compared to more attacking positions. Wide midfielders with a faster or slower maximal sprint speed (MSS, fastest 10 m split during a 40 m sprint test), were both reported to achieve ~90% of their MSS during a match (Mendez-Villanueva, et al., 2011b). Although a similar percentage of MSS (90%) was achieved in games by central defenders with a slower MSS, central defenders with a faster MSS only reached ~84% of MSS. It was theorised that the expression of a player's maximal running speed may be restrained due to the tactical role of the central defender position compared to that of the wide midfielder. The information in this study supports this theory as non-central positions with offensive duties (wide defenders, wide midfielders and forwards) performed more sprints than central positions with defensive duties (central defenders, central midfielders).

It could be assumed that the central roles may place an emphasis on the ability to accelerate, however, in this study the number of maximal accelerations were fairly homogenous across all positions with the exception of wide defenders (Figure 4-3). Wide defenders are often required to perform both defensive and offensive duties resulting in constant back and forth

movement which may explain the high number of accelerations and sprints undertaken. It should be acknowledged that of the players in the wide defender position, one player contributed 11 cases, therefore data for this position should be interpreted with caution as it may not be representative of the population. Forwards performed a similar high number of sprint efforts. As a forwards opponent is often the last outfield line of defence, if a forward evades their opponent they may be presented with a large amount of space to run. Although wide midfielders are known to perform a greater number of sprints than other positions (Di Salvo, et al., 2010), the lower values compared to wide defenders and forwards in this study may be a result of the tactical approach of the teams. Both teams placed an emphasis on the wide defenders playing more offensively, resulting in the wide midfielders cutting into more central positions and limiting the available space to sprint. Unfortunately the team formations were not recorded, which is an important consideration as this can influence player movements (Bradley, et al., 2011). Importantly, all positions performed significantly more acceleration than sprint efforts. This suggests that the ability of players to frequently accelerate is an important characteristic of gameplay despite position.

Elite soccer players frequently undertake maximal acceleration efforts during match-play. Not only did players predominantly accelerate from a lower speed than what is typically defined as high-speed running (< 4.17 $m.s^{-1}$) but approximately half the efforts performed did not exceed this speed. This supports the inclusion of acceleration information when profiling player movements to provide a more accurate representation of the high-intensity activity undertaken during a match. The identification of position specific acceleration patterns can assist sport scientists and conditioning staff to develop position-specific conditioning drills. Researchers should consider the accuracy of the analysis system utilised when deriving acceleration information, as the results of study one showed that older technologies may be restricted in the data they can provide (See Chapter 3). The improved accuracy of systems, such as 10 Hz GPS and high-frequency radio technology, would allow a more detailed analysis of match accelerations (Frencken, Lemmink, & Delleman, 2010). The magnitude of the accelerations is related to the sampling window. If other practitioners use a different

sampling window this may change the magnitude of the accelerations recorded. Future research should explore the relationship between acceleration and other variables, such as standard of competition, level of opposition and the technical activities/match outcomes associated with its occurrence.

CHAPTER 5. STUDY 3: THE EFFICACY OF SODIUM BICARBONATE INGESTION AND REPEAT SPRINT TRAINING FOR IMPROVING ACCELERATION CAPACITY AND K^+ REGULATION DURING REPEAT SPRINT EXERCISE

Being prepared for submission:

Varley, M. C., McKenna, M. J., Anderson, M., Stepto, N. K. & Aughey, R. J. (2012). The efficacy of sodium bicarbonate ingestion and repeat sprint training for improving acceleration capacity and K^+ regulation during repeat sprint exercise. (Being prepared for submission to European Journal of Applied Physiology)

5.1 Introduction

The intermittent nature of team sports involves the performance of multiple high-intensity activities including acceleration, sprint and high-speed efforts (see Chapter 4). Despite their short duration of < 4 s (Mohr, Krustrup, & Bangsbo, 2003; Withers, et al., 1982) these efforts are important in the outcome of decisive match activities such as moving past an opponent and creating or stopping goal scoring opportunities (Reilly, Bangsbo, & Franks, 2000). Further, players may experience intense periods of play that require the repeated performance of these efforts (Bradley, et al., 2009b; Mohr, Krustrup, & Bangsbo, 2003). Therefore, not only is it important to maximally accelerate and to achieve a high speed but so too is the ability to reproduce these efforts. However, the investigation of interventions to improve the performance of repeated maximal efforts of extremely short duration (i.e. < 6 s) has received little attention.

Intense exercise results in multiple ionic disturbances, specifically an increase in the efflux of K^+ from contracting muscle leading to an increase $[K^+]_e$ (for review see Sejersted & Sjøgaard, 2000). The peak in plasma $[K^+]_{pl}$ following both a single and repeated 6 s sprints (15 x 6 s

sprints with 60 s recovery) is relatively low (5.5 mM) (Mohr, et al., 2007). During intense exercise muscle interstitial $[K^+]$ can exceed that of $[K^+]_{pl}$ by as much as 3 - 9 mM (Nielsen, et al., 2004; Street, et al., 2005). Increased activation of the Na^+,K^+-ATPase can attenuate the net cellular loss of K^+ and increase its reuptake into the contracting muscle (Clausen, Andersen, & Flatman, 1993; Nielsen & Clausen, 1997). However, maximal *in-vitro* activity of the Na^+,K^+-ATPase is depressed during fatiguing exercise (Aughey, et al., 2006; Fraser et al., 2002). This may lead to a faster accumulation of $[K^+]_e$ to high levels which can impair muscle excitability and depress force production, accelerating the onset of fatigue (Cairns, Flatman, & Clausen, 1995; Cairns, et al., 1997; McKenna, Bangsbo, & Renaud, 2008). A reduction in $[K^+]_{pl}$ of ~0.4 mM during dynamic finger flexion exercise was associated with a 25% greater time to fatigue (Sostaric, et al., 2006), suggesting small decreases in $[K^+]_{pl}$ can enhance muscular performance. However, it is unclear whether a reduction in $[K^+]_{pl}$ during maximal short duration exercise would result in improvements in performance, such as an increased capacity to accelerate or to maintain a high rate of acceleration over repeated efforts.

Repeat sprint training can improve both peak speed and the rate of acceleration (Buchheit, et al., 2010b; Spinks, et al., 2007) achieved in single sprints. Multiple-set RSE may be more specific to the movements encountered during team sports, as it involves both short (< 30 s) and long (> 4 min) recovery periods. Four weeks of multiple-set RST (3 sets of 5 x 4 s sprints with 20 s recovery between sprints and 4.5 min recovery between sets) improved peak speed and acceleration, by up to 6 and 22%, respectively (Serpiello, et al., 2011). Peak and mean speed and acceleration were also improved across each set of RSE reflecting an improvement in the capacity to reproduce high-intensity efforts (Serpiello, et al., 2011). Further, RST may improve K^+ regulation. Following repeat sprint and intermittent all-out training involving 6 or 30 s maximal efforts respectively, peak $[K^+]_{pl}$ was unchanged despite increased work performed (McKenna, et al., 1993; Mohr, et al., 2007). This is may be due to a greater K^+ reuptake into the muscle via increased content and/or activation of the Na^+,K^+-ATPase, resulting in both improved K^+ regulation and performance (McKenna et al., 1996; Mohr, et

al., 2007). This is supported by an increase in muscle Na^+,K^+-ATPase content following 7 weeks of intermittent all-out training (McKenna, et al., 1993).

Ergogenic agents such as $NaHCO_3$ have been used to improve performance (Bishop, et al., 2004; Raymer, et al., 2004; Siegler, et al., 2010; Sostaric, et al., 2006) and lower $[K^+]_{pl}$ at rest and during exercise (Lindinger, et al., 1999; Raymer, et al., 2004; Sostaric, et al., 2006; Yamanaka et al., 2011). Following $NaHCO_3$ ingestion prior to exhaustive exercise, there was a greater reuptake of K^+ into muscle at fatigue and during recovery, suggesting an increase in muscle Na^+,K^+-ATPase activity (Sostaric, et al., 2006). A lower $[K^+]_{pl}$ following $NaHCO_3$ ingestion was associated with improved time to fatigue and peak power output during exhaustive exercise (Raymer, et al., 2004; Sostaric, et al., 2006) but not performance time or power output during endurance cycling (Stephens, et al., 2002). Ingestion of $NaHCO_3$ prior to intermittent maximal exercise (3 x 30 s interspersed by 180s recovery) lowered capillary $[K^+]$ at rest and 150 s into each recovery, however, total distance was only improved when $NaHCO_3$ ingestion was coupled with an active rather than passive recovery (Siegler, et al., 2010). The ingestion of $NaHCO_3$ prior a single set of RSE (5 x 6 s cycle sprints occurring every 30 s) (Bishop, et al., 2004) increased total work and power output. In contrast, no improvements were observed in mean or peak running speed during RSE (10 x 6 s sprints interspersed with 30 s recovery) performed on a non-motorised treadmill (Gaitanos, et al., 1991). To date no study has investigated the effects of $NaHCO_3$ on $[K^+]_{pl}$ during repeat maximal efforts of < 6 s duration. Therefore, it remains unclear whether $NaHCO_3$ ingestion can lower $[K^+]_{pl}$ and/or increase acceleration and speed during short duration maximal efforts common to team sports.

The physiological adaptations to training can diverge with different types of training, due to the specific metabolic response to exercise type. If acute ingestion of $NaHCO_3$ can alter the metabolic response to exercise then a different magnitude of adaptation may occur with the same type of training. The only study that has investigated the acute ingestion of $NaHCO_3$ prior to each training session, employed 8 weeks of interval training involving 2 min cycle intervals (Edge, Bishop, & Goodman, 2006). Following training, a greater improvement in

lactate threshold and time to fatigue was observed in the $NaHCO_3$ compared to the placebo group. However, the physiological and performance adaptations to chronic $NaHCO_3$ ingestion during RST are unknown. This information would be useful to team sport conditioning staff striving to optimise methods to improve the ability of athletes to perform repeated high-intensity efforts.

Therefore the main aims of this study were to investigate whether acute $NaHCO_3$ ingestion prior to RSE improves acceleration and speed and lowers $[K^+]_{pl}$ during RSE exercise and recovery. A secondary aim was to investigate whether chronic $NaHCO_3$ ingestion prior to each training session during 4 weeks of RST would enhance the improvements in performance associated with RST and lead to different physiological adaptations following RST compared to placebo ingestion.

5.2 Methods

5.2.1 Participants

Fourteen healthy young adults (10 male, 4 female) were randomly assigned to either an experimental (EXP) group, who ingested $NaHCO_3$ prior to RSE, or a control (CON) group, who ingested calcium carbonate ($CaCO_3$) prior to RSE, and subsequently undertook 4 weeks of RST. The baseline physical characteristics of the participants are shown in Table 5-1. All participants were recreationally active and involved in various club level sports (soccer, netball, Australian football). The study was approved by the Victoria University Research Ethics Committee and all participants provided informed consent before participating.

Table 5-1 Participants' baseline physical characteristics

Group	Age (yr)	Height (cm)	Body mass (kg)	$\dot{V}O_{2peak}$ (mL kg^{-1} min^{-1})
$NaHCO_3$ (*n* =7)	21.3 ± 1.5	174 ± 10	70.0 ± 8.1	51.6 ± 5.1
Placebo (*n* =7)	20.6 ± 1.7	172 ± 10	68.1 ± 8.6	55.0 ± 8.8

Data are mean ± SD. No significant differences between group were observed for all measures

5.2.2 Experimental design

The experimental design is presented in Figure 5-1. Participants attended the laboratory on sixteen separate occasions. During the first three visits participants undertook an incremental exercise test on a treadmill on the first visit and two familiarisation sessions of RSE on the second and third visit. All sessions were separated by at least 48 h and familiarisation sessions were conducted one week apart. In a randomised, single-blind design, participants were assigned to either the EXP or CON group. At least four days after the second familiarisation, participants completed an initial pre-training RSE session (PRE) in which both groups ingested $CaCO_3$ prior to RSE. After a one week washout period, to determine the acute effects of $NaHCO_3$ supplementation, participants completed a second pre-training RSE session (CON). Prior to this RSE, the EXP group ingested $NaHCO_3$ and the CON group ingested $CaCO_3$. Data from the CON group was not collected during the ACUTE trial, as they were only attending the second session to ensure consistency between groups in terms of the number of training sessions attended. At least 72 h after ACUTE both groups commenced four weeks of RSE training comprising 3 sessions per week, each separated by at least 48 hours for a total of 12 sessions, with each group ingesting their respective supplement ($CaCO_3$ or $NaHCO_3$) prior to each session. Forty-eight hours after the final training session all participants performed a post-training RSE session (POST) during which both groups ingested $CaCO_3$ prior to exercise. No $NaHCO_3$ was ingested during PRE and POST testing by either group. Participants were instructed to refrain from consuming alcohol, caffeine and performing vigorous exercise for 48 h prior to all testing sessions. All participants were asked

to fast for 12 hours prior to PRE, ACUTE and POST due to muscle biopsies performed pre- and post-exercise (Part of a larger study, data not included in this thesis). All testing sessions were performed at the same time of day (8:00 – 10:00am) to control for diurnal effects (Giacomoni, Billaut, & Falgairette, 2006; Zarrouk et al., 2012).

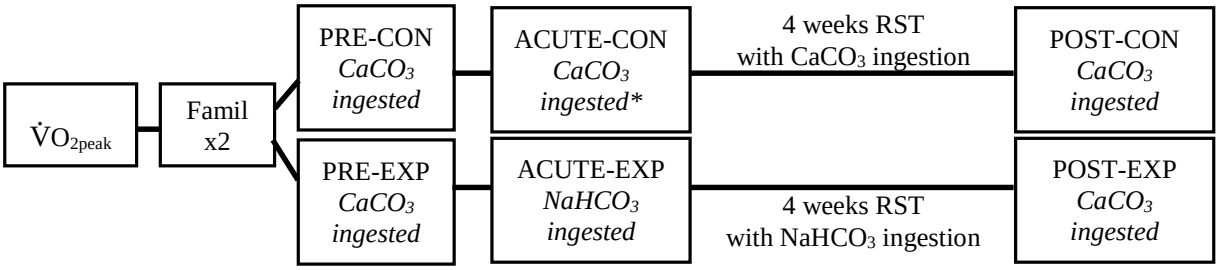

Figure 5-1 A diagrammatic representation of the experimental design. V̇O2peak = incremental exercise test, Famil = repeat sprint exercise familiarisation, PRE, ACUTE and POST = CaCO3 or NaHCO3 ingested 90 min prior to repeat sprint exercise, RST = repeat-sprint training. *No data collected during trial

5.2.3 Incremental exercise test

The incremental exercise test was performed on a motorised treadmill (Quinton Q65, Seattle, WA, USA) with speed commencing at 8 km.hr^{-1} and subsequently increased by 1 km.hr^{-1} every minute, with no gradient, until volitional exhaustion. Expired gases fractions and volumes were analysed using a calibrated custom-made metabolic cart (for details see Serpiello, et al., 2011). The $\dot{V}O_{2peak}$ was calculated as the average of the two highest values in two consecutive 15 s periods. The speed at $\dot{V}O_{2peak}$ ($v\dot{V}O_{2peak}$) was the speed at the final 1-min stage to be completed in full.

5.2.4 Familiarisation trials

At least 3 days after completing the incremental exercise test, participants performed the first RSE familiarisation trial. This consisted of a 4-min standardised warm up on a motorised treadmill at a running speed of 60% $v\dot{V}O_{2peak}$, followed by three warm-up runs on a non-motorised treadmill (Woodway Force, Waukesha, WI, USA) each comprising two 4 s runs at 13 km.hr^{-1}, with an intervening 20 s passive recovery, followed by 1 min of rest with an ensuing final 4 s run at 15 km.hr^{-1}. Following 1 min of passive rest RSE began and comprised

of three sets of five, 4 s maximal sprints with 20 s of passive recovery between sprints and 4.5 minutes of passive rest between sets (Serpiello, et al., 2011). Participants were instructed to run maximally during each sprint and were verbally encouraged throughout. A similar external verbal motivation was given during all RSE sessions. This protocol was repeated for all subsequent familiarisation, training and testing sessions however the three warm-up runs were performed at 70%, 70% and 90% respectively, of the peak speed attained during the first familiarisation trial. One week after the first familiarisation, participants completed a second familiarisation trial.

5.2.5 Supplementation

Participants prior to each RSE session ingested either $NaHCO_3$ or $CaCO_3$. The dosage was either 0.3 $g.kg^{-1}$ of $NaHCO_3$ encased in 22 – 30 gelatin capsules (Sodibic, Aspen Pharmacare, St Leonards, NSW, Australia) or an equal number of placebo capsules containing $CaCO_3$. Both $NaHCO_3$ and $CaCO_3$ capsules were ingested with water *ad libitum* over a 1 h period, in 3 even doses at 90, 60 and 30 min prior to exercise. This dosage and ingestion protocol was chosen for several reasons. First, 0.3 $g.kg^{-1}$ of $NaHCO_3$ ingested 90 min prior to exercise lowered $[K^+]_{pl}$ during exercise (Raymer, et al., 2004). Second, this ingestion period has a more practical application to team sport athletes who may be limited in the time available to ingest a supplement prior to each training session. Pilot testing determined that this protocol did not result in any gastrointestinal disturbances.

5.2.6 Repeat sprint exercise trials

During PRE, ACUTE and POST participants arrived at the laboratory 2 hours prior to commencement of the RSE. A 20 or 22G catheter (Optiva, Smiths Medical, Rossendale, UK) was inserted into an antecubital vein. Participants remained in a supine position from 10 minutes prior to ingestion until the warm-up on the motorised treadmill and again throughout the entire recovery period. A blood sample was drawn prior to supplement ingestion (-90), and 80 min later just prior to the warm up (-10), immediately prior to RSE, after each set of sprint, and at 1, 5, 10, 20 and 30 min in recovery.

5.2.7 Blood analysis

Blood samples were drawn into a 3mL syringe containing lithium heparin. Blood samples were immediately analysed in duplicate for plasma electrolytes ($[K^+]_{pl}$ and $[Na^+]_{pl}$) and acid-base status (plasma pH and bicarbonate concentration $[HCO_3^-]_{pl}$) using an automated blood gas analyser (Rapidpoint® 405, Siemans medical Solutions Diagnostic, Tarrytown NY, USA) and for plasma lactate concentration ($[Lac^-]_{pl}$) using an automated analyser (2300 STAT plus, YSI, Inc., Yellow Springs, OH). Total haemoglobin (Hb) and haematocrit (Hct) were measured in duplicate using an automated haematology analyser (Sysemex K-800, TOA Medical Electronics, Kobe, Japan) to determine the change in plasma volume following ingestion, during exercise and recovery.

5.2.8 Repeat sprint exercise performance measures and reliability

For each sprint during RSE each of acceleration, peak and mean speed and mean power were determined. All measurement data were acquired at a sampling frequency of 200 Hz. The calibration and adjustment of the non-motorised treadmill and calculation of performance measures were performed as previously detailed (Serpiello, et al., 2011). The commencement of each sprint was identified by the first movement above 1 $m.s^{-1}$, to ensure consistency in the measure. Acceleration was calculated as the rate of change in speed during the first 0.5 s immediately after attaining 1 $m.s^{-1}$. This period was chosen to reflect maximal acceleration since acceleration began to plateau over longer periods (Serpiello, et al., 2011).

Due to an evident learning effect between the two familiarisation sessions and the ingestion of a supplement during all subsequent training sessions, measures of reliability for the RSE performance measures were unable to be calculated. However, previous research from this laboratory has determined the reliability for these measures using the same protocol and equipment and a group of participants with similar characteristics to those used in this study (Serpiello, et al., 2011). Reliability calculated as the typical error expressed as a CV were 3.5% and 2.6% for peak and mean speed, 4.7% for mean power and 7.6% for acceleration (Serpiello, et al., 2011). In the current study peak power was not used due to the poor reliability of the measure (CV of 10.8%). To assess if any changes in performance were

greater than the smallest practically important effect, the smallest worthwhile change was calculated for each performance measure (0.2 multiplied by the between-subject standard deviation expressed as a CV (%)) (Batterham & Hopkins, 2006). The smallest worthwhile change was 2.4% for peak and mean speed and 4.1% for acceleration and mean power.

5.2.9 Calculations

To account for differences in $[K^+]_{pl}$ pre-ingestion between trials and groups the change in $[K^+]_p$ ($\Delta[K^+]_{pl}$) from pre-ingestion (-90) were calculated following ingestion, during exercise and recovery. Changes from pre-ingestion (-90) resting levels in plasma volume were calculated following ingestion, during and after exercise, from changes in [Hb] and Hct, as previously described (McKenna et al., 1997). Raw data for changes in plasma volume are provided in APPENDIX C.

5.2.10 Statistical analysis

Data are presented as mean ± SD. For datasets with missing values (less than 1% of data missing) a multiple imputation data replacement technique was used considering five imputations (Schafer, 1997). Missing values were at random and due to haemolysis of blood samples or equipment error. To assess the effect of acute $NaHCO_3$ supplementation (ACUTE) compared to placebo (PRE) on blood gas and acid-base measures over time a two-way repeated measures ANOVA was used. Only the EXP group were included in this analysis (n = 7). Paired t-tests were used to determine specific differences over time and between supplementation conditions. To examine the effects of RSE training and supplementation on blood gas and acid-base measures over time (PRE vs. Post) a two-way repeated measures ANOVA was used. Paired t-tests were used to determine specific differences over time and from pre- to post-training for each group. Independent t-tests were performed to explore specific differences between groups. Significance was assumed at P=0.05.

All RSE performance measures were log transformed to reduce the bias due to non-uniformity of error. The magnitude of the within-group changes in performance and between-group differences in the changes in performance, were assessed using effect size (ES) statistic with 90% confidence intervals (CI) and percentage change (Batterham & Hopkins, 2006;

Hopkins, et al., 2009). Threshold values for ES statistic were as follows: < 0.2; trivial, 0.2 to 0.6; small, 0.6 to 1.2; moderate, 1.2 to 2.0; large, > 2.0; very large (Batterham & Hopkins, 2006). For within/between group comparisons, the chances that the true (unknown) values for each training and supplement combination were beneficial/better (greater than the smallest worthwhile change), unclear or detrimental/poorer for RSE performance were calculated. Quantitative chances of a beneficial/better or detrimental/poorer change in performance were assessed qualitatively as follows: < 1%, almost certainly not; 1 to 5%, very unlikely; 5 to 25%, unlikely, 25 to 75%, possible; 75 to 95%, likely; 95 to 99%, very likely; > 99%, almost certain. If the chance of having beneficial/better or detrimental/poorer performances were both > 5%, the true difference was assessed as unclear (Batterham & Hopkins, 2006; Hopkins, et al., 2009).

5.3 Results

5.3.1 Performance response to $NaHCO_3$ ingestion prior to repeat sprint exercise

The ingestion of $NaHCO_3$ prior to RSE resulted in only trivial differences in all RSE performance measures compared to the PRE-EXP trial (ES; -0.05 to 0.02). Furthermore, there were only trivial differences in the between-set decrements in performance for all RSE measures following $NaHCO_3$ ingestion compared to the PRE-EXP trial (ES; 0.03 to 0.05).

5.3.2 Physiological response to NaHCO3 ingestion prior to repeat sprint exercise

5.3.2.1 Acid base balance

Plasma pH decreased during and immediately after RSE and began to increase after 2 min of recovery (time main effect, $P<0.001$, Figure 5-2) in the PRE-EXP and ACUTE-EXP trials. Following $NaHCO_3$ ingestion pH was greater than in the PRE-EXP trial prior to, throughout exercise and recovery ($P=0.001$). Plasma [HCO_3^-] decreased immediately after each RSE set, beginning to increase after 5 min of recovery (time main effect $P<0.001$, Figure 5-2) in the PRE-EXP and ACUTE-EXP trials. Plasma [HCO_3^-] was greater during following $NaHCO_3$ ingestion compared to the PRE-EXP trial ($P=0.002$). During exercise $[Lac^-]_{pl}$ increased (time main effect ($P<0.001$, Figure 5-2) in the PRE-EXP and ACUTE-EXP trials, however there was no difference in $[Lac^-]_{pl}$ between trials ($P=0.281$).

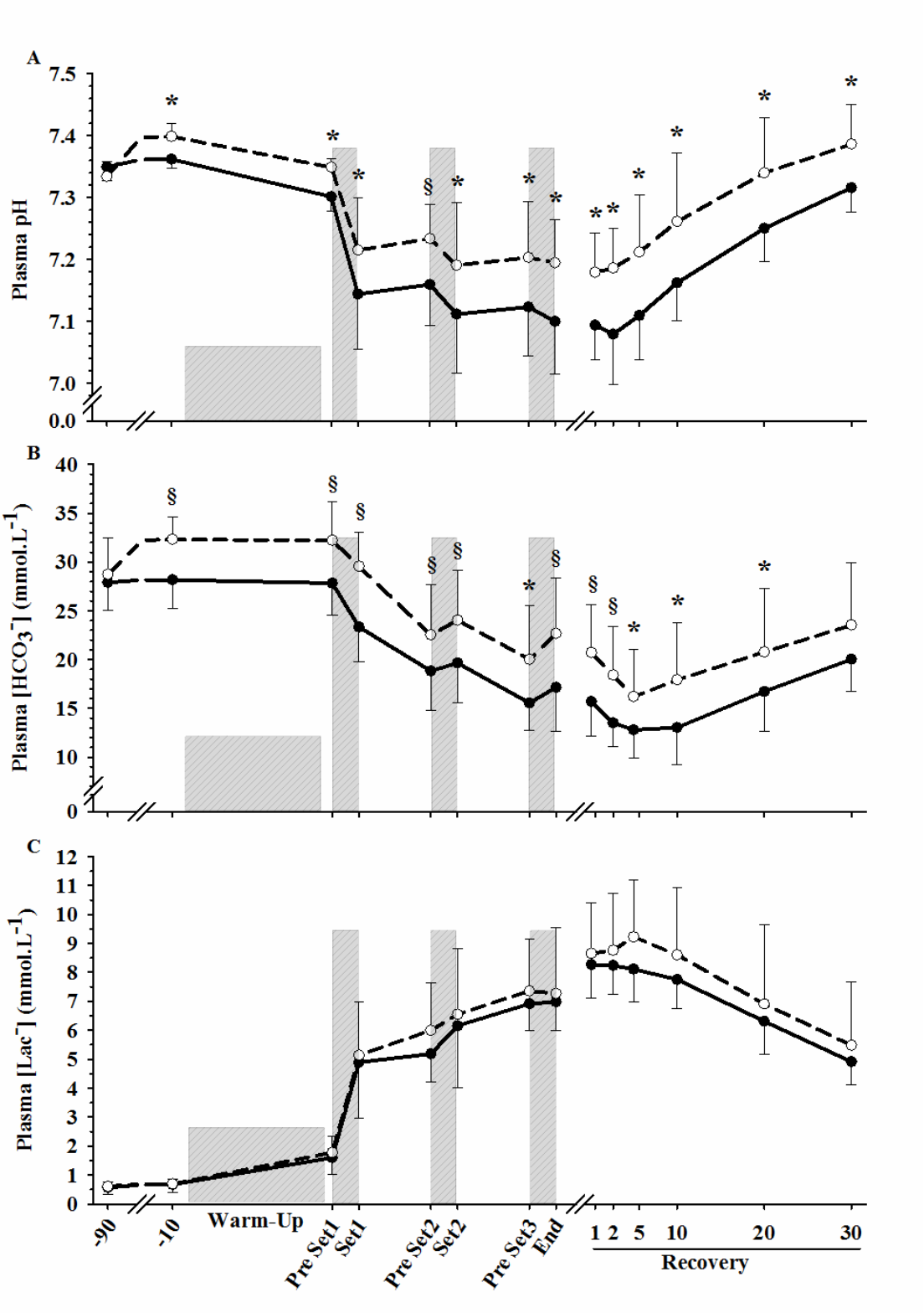

Figure 5-2 Pre-training venous plasma pH (A), plasma [HCO_3^-] (B) and plasma [Lac^-] (C) during RSE and recovery for EXP group (n=7) during PRE-EXP (placebo ingestion, closed circles) and ACUTE-EXP ($NaHCO_3$ ingestion, open circles). Data are mean ± SD. * = greater than PRE-EXP (P<0.05), § = greater than PRE-EXP (P<0.01). Shaded area indicates exercise

5.3.2.2 Plasma electrolytes

Plasma [Na^+] was increased immediately after each RSE set and decreased during the recovery period of each set and during the post-exercise recovery (P<0.001, Figure 5-3) in the PRE-EXP and ACUTE-EXP trials. Following $NaHCO_3$ ingestion $[Na^+]_{pl}$ was greater than during the PRE-EXP trial resulting in a main effect for supplement (P=0.005).

Immediately after each RSE set $[K^+]_{pl}$ increased and then decreased during each recovery period (time main effect P<0.001 Figure 5-3) in the PRE-EXP and ACUTE-EXP trials. The peak $[K^+]_{pl}$ occurred after the first set of RSE in both trials which was 4.82 ± 0.51 mM in PRE-EXP and 5.01 ± 0.29 in ACUTE-EXP. There was no difference in $[K^+]_{pl}$ between trials (P=0.957). The $\Delta[K^+]_{pl}$ followed a similar pattern over time as $[K^+]_{pl}$, with a time main effect (P<0.001) in the PRE-EXP and ACUTE-EXP trials. There was no difference in $\Delta[K^+]_{pl}$ between trials (P=0.110). However, there was a trend for $\Delta[K^+]_{pl}$ to be lower at all recovery periods following $NaHCO_3$ ingestion compared to PRE-EXP (Figure 5-3). Effect sizes for this trend ranged from 0.85 to 2.95.

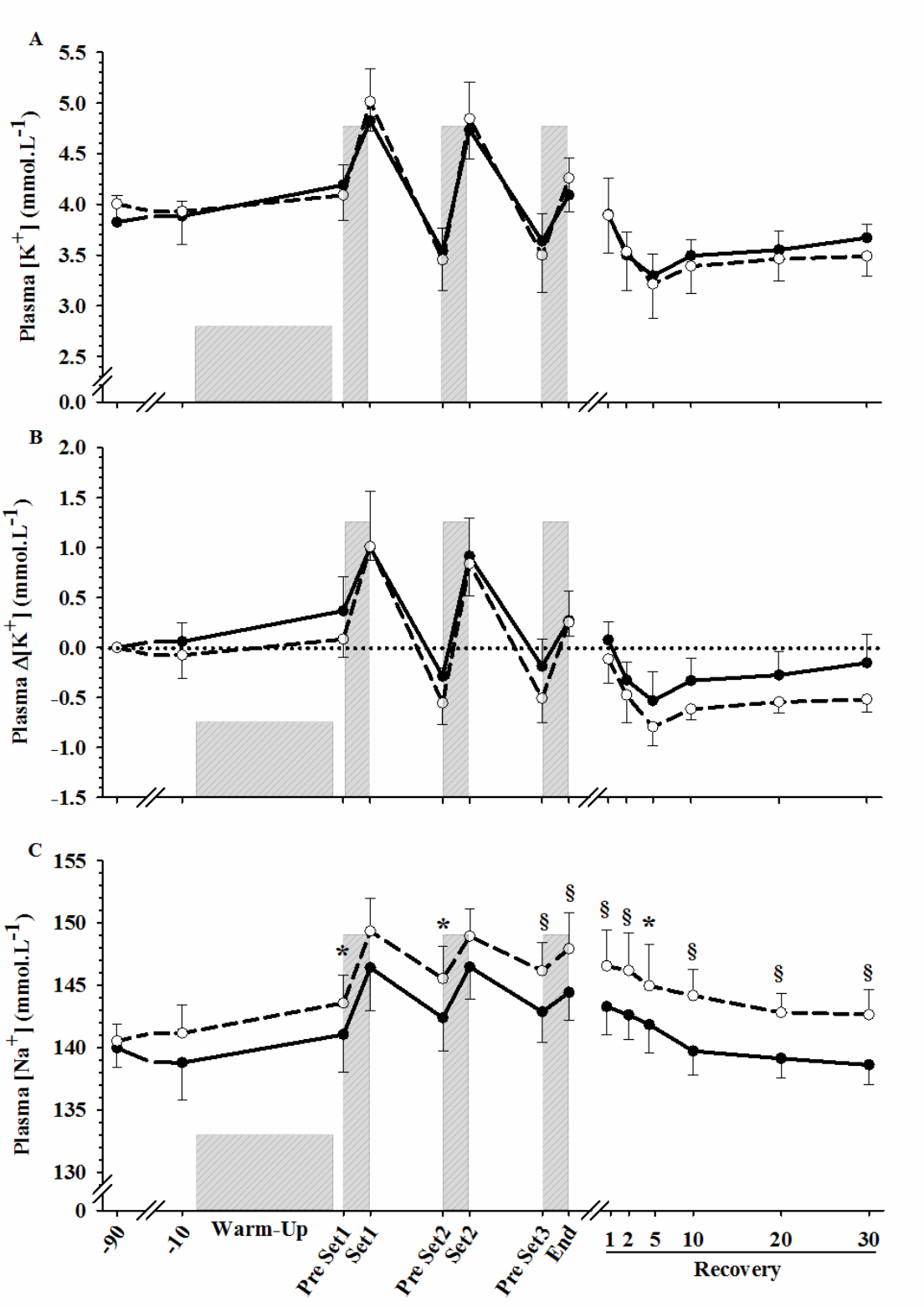

Figure 5-3 Pre-training venous plasma [K^+] (A), plasma Δ[K^+] (B) and plasma [Na^+] (C) during RSE and recovery for EXP group (n=7) during PRE-EXP (placebo ingestion, closed circles) and ACUTE-EXP ($NaHCO_3$ ingestion, open circles). Data are mean ± SD. * = greater than PRE-EXP (P<0.05), § = greater than PRE-EXP (P<0.01). Shaded area indicates exercise

5.3.3 Performance response to repeat sprint training

The pre and post-training RSE performance data for both groups is presented in Table 5-2. Only trivial differences existed between groups for all performance measures in set 1 during pre-training, however the EXP group had a greater peak and mean speed and mean power in set 3 (3.4 ± 10.9%, ES; 0.29 ± 0.90, 3.7 ± 10.6% ES; 0.33 ± 0.90 and 8.1 ± 18.8% ES; 0.41 ± 0.90, respectively) and greater acceleration in set 2 and 3 (5.1 ± 18.2%, ES;0.27 ± 0.90 and 9 ± 16.4%, ES; 0.51 ± 0.90, respectively). Performance reduced across the 3 sets of RSE during pre-training and post-training in both groups (Table 5-3).

Peak and mean speed, mean power and acceleration improved in the CON group by a small magnitude in each set of RSE following RST whereas the EXP group had small improvements only during set 2 with the exception of mean power (Figure 5-4). The between-group differences in the magnitude of the change in RSE performance measures following training are presented in Table 5-2. There was no difference in the decrement in performance from set 1 to set 3 following RST in either group for all performance measures (ES; -0.04 to 0.16).

Table 5-2 Mean values of repeat sprint exercise performance for CON and EXP groups during PRE and POST sessions and the differences in the magnitude of the change in performance following four weeks of RST in combination with $NaHCO_3$ or placebo ingestion prior to each session

		CON (n = 7)		EXP (n = 7)		Differences in the changes observed following RST for EXP compared with CON			
	Set	PRE	POST	PRE	POST	Difference in the change (%)	Effect Size ± 90% CI	% chances of better/ trivial/poorer effect	Qualitative descriptor
Acceleration ($m.s^{-2}$)	1	3.57 ± 0.58	3.82 ± 0.64	3.73 ± 0.72	3.90 ± 0.70	-2.1 ± 10.5	-0.11 ± 0.51	15/48/37	unclear
	2	3.49 ± 0.56 †	3.72 ± 0.61	3.67 ± 0.61	3.87 ± 0.64	-1.1 ± 5.8	-0.06 ± 0.29	7/73/20	unclear
	3	3.23 ± 0.50 †	3.49 ± 0.60 †	3.53 ± 0.54 †	3.65 ± 0.50	-3.8 ± 7.7	-0.20 ± 0.38	4/47/49	possibly less beneficial
Peak Speed ($m.s^{-1}$)	1	5.03 ± 0.50	5.25 ± 0.51	5.04 ± 0.60	5.16 ± 0.62	-1.8 ± 2.4	-0.16 ± 0.20	1/64/35	possibly less beneficial
	2	4.90 ± 0.49	5.09 ± 0.49 †	4.89 ± 0.59	5.07 ± 0.56	-0.4 ± 2.7	-0.03 ± 0.22	4/85/11	unlikely less beneficial
	3	4.64 ± 0.34 †	4.93 ± 0.43 †	4.81 ± 0.58 †	4.92 ± 0.52 †	-3.7 ± 5.0	-0.32 ± 0.41	2/28/69	possibly less beneficial
Mean Speed ($m.s^{-1}$)	1	4.27 ± 0.43	4.44 ± 0.44	4.29 ± 0.52	4.40 ± 0.53	-1.6 ± 2.9	-0.13 ± 0.24	2/66/32	possibly less beneficial
	2	4.16 ± 0.41	4.32 ± 0.43	4.18 ± 0.50	4.33 ± 0.49	0.0 ± 3.0	-0.00 ± 0.24	9/32/9	unclear
	3	3.93 ± 0.32 †	4.17 ± 0.37 †	4.09 ± 0.47 †	4.19 ± 0.42 †	-3.1 ± 4.5	-0.26 ± 0.37	2/35/63	possibly less beneficial
Mean Power (W)	1	745 ± 131	788 ± 159	756 ± 150	754 ± 169	-5.8 ± 5.6	-0.29 ± 0.27	0/28/72	possibly less beneficial
	2	704 ± 119	739 ± 144	715 ± 142	728 ± 155	-3.0 ± 6.2	-0.15 ± 0.30	3/60/37	possibly less beneficial
	3	626 ± 88	684 ± 116	684 ± 132	678 ± 129	-8.8 ± 9.6	-0.45 ± 0.45	1/16/83	likely less beneficial

Both groups ingested $CaCO_3$ prior to exercise during PRE and POST testing, All values are mean ± SD, † = small difference compared to EXP (ES = 0.2 – 0.6)

Table 5-3 Percentage decrement in RSE performance from set 1 before and after four weeks of RST in combination with $NaHCO_3$ or placebo ingestion prior to each session

		CON (n=7)		EXP (n=7)	
	Set	**PRE**	**POST**	**PRE**	**POST**
Acceleration (%)	2	-2.2 ± 5	-2.7 ± 6.4	-1.0 ± 3.5	-0.5 ± 4.7
	3	-9.3 ± 9.4 [a, †]	-8.8 ± 6.7 [a]	-4.8 ± 5.8 [a]	-5.9 ± 7.0 [a]
Peak Speed (%)	2	-2.6 ± 1.3 [a]	-3.1 ± 1.1 [a]	-2.8 ± 2.2	-1.8 ± 1.8
	3	-7.6 ± 3.9 [b, †]	-6.0 ± 2.2 [a]	-4.4 ± 2.3 [a]	-4.6 ± 3.3 [a]
Mean Speed (%)	2	-2.5 ± 1.5 [a]	-2.8 ± 1.9	-2.6 ± 2.1	-1.4 ± 1.9
	3	-7.7 ± 4.1 [b, †]	-6.2 ± 3.0 [a]	-4.6 ± 2.3 [a]	-4.5 ± 3.5 [a]
Mean Power (%)	2	-5.4 ± 3.3 [a]	-6.2 ± 2.9 [a]	-2.6 ± 2.1	-3.3 ± 3.4
	3	-15.4 ± 7.3 [b, †]	-12.7 ± 5.3 [a]	-4.6 ± 2.3 [a]	-9.5 ± 6.7 [a]

Both groups ingested $CaCO_3$ prior to exercise during PRE and POST testing, All values are mean ± SD, [a] = small reduction compared to set 1 (ES = 0.2 – 0.6), [b] = moderate reduction compared to set 1 (ES = 0.6 – 0.8), [†] = small difference compared to EXP group

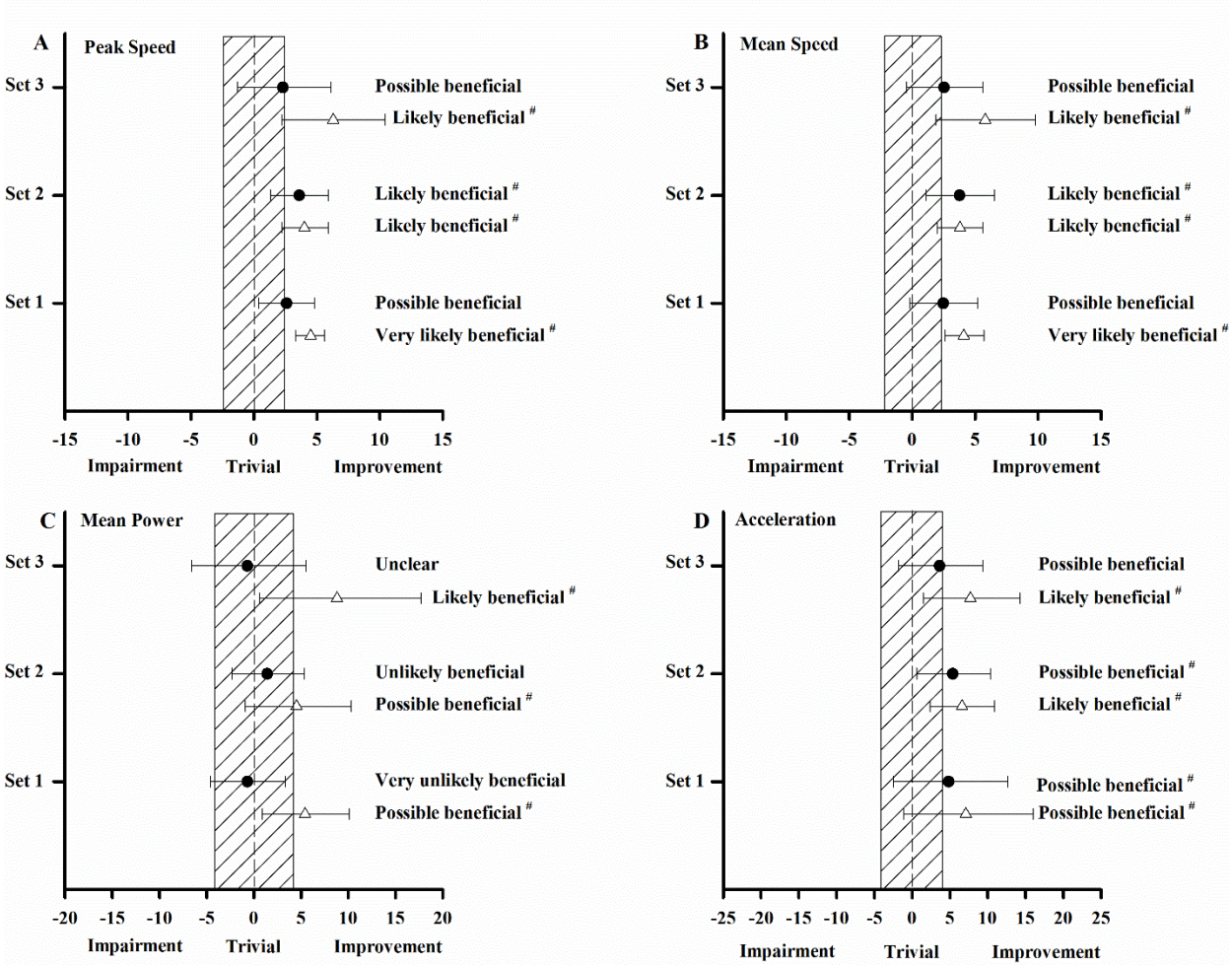

Figure 5-4 Within-group relative changes for peak speed (A), mean speed (B), mean power (C) and acceleration (D) following four weeks of repeat sprint training in combination with $NaHCO_3$ (EXP group; n = 7; closed circles) or placebo (CON group; n = 7; open triangles) ingestion prior to each session (bars indicate uncertainty in the true mean changes with 90% confidence intervals). Trivial area was calculated from the smallest worthwhile change (see methods), # = moderate effect size (0.2 – 0.6). Both groups ingested $CaCO_3$ prior to exercise during PRE and POST testing

5.3.4 Physiological response to repeat sprint training

5.3.4.1 Acid base balance

Differences in plasma pH were observed according to training group (P=0.010) and over time (P<0.001). An interaction effect for training*time (P=0.002) was detected, however there was no effect for supplement (P=0.267). Post-hoc tests indicated plasma pH was significantly lower at several time points post-training in the CON group, however no specific differences were detected in the EXP group (Figure 5-5).

Whilst no effect for training or supplement was detected in $[HCO_3^-]_{pl}$ (P=0.390 and P=0.925, respectively) and $[Lac^-]_{pl}$ (P=0.0.57 and P=0.501, respectively), there was a main effect for time (P<0.001) (Data not shown).

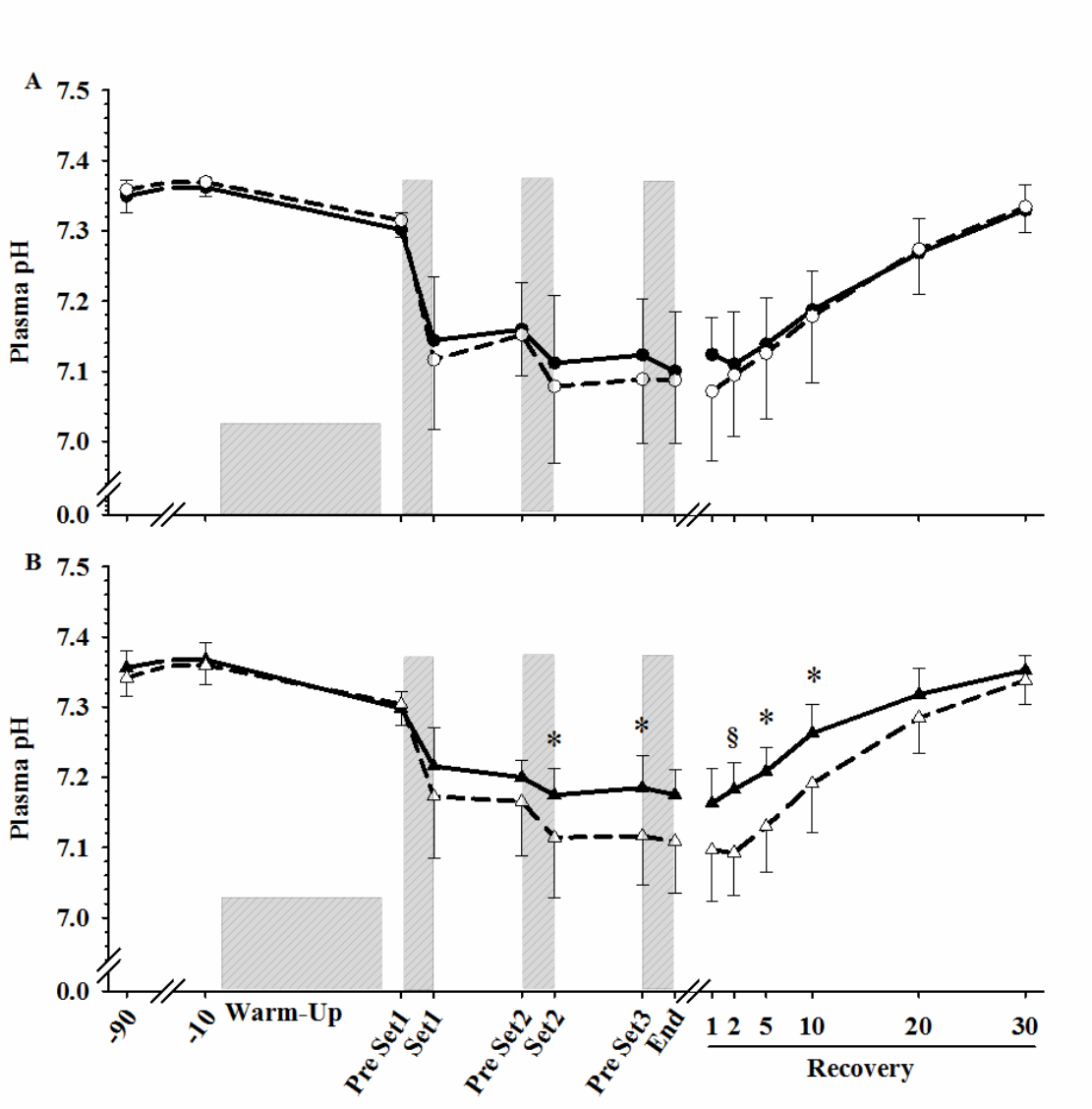

Figure 5-5 Venous plasma pH during RSE and recovery during PRE (closed symbols) and POST (open symbols) testing for EXP (circles), (A) and CON (triangles), n=7 (B) groups. Data are mean ± SD. * = greater than pre-training (P<0.05), § = greater than pre-training (P<0.01). Both groups ingested $CaCO_3$ prior to exercise during PRE and POST testing. Shaded area indicates exercise

5.3.4.2 Plasma electrolytes

There were changes in $[Na^+]_{pl}$ for training (P=0.007) and over time (P<0.001) but no significant changes for supplement (P=0.380). Post-hoc tests indicated that $[Na^+]_{pl}$ was significantly greater at several time points post-training in the CON group and at 30 min recovery in the EXP group (Figure 5-6).

There was a main effect of $[K^+]_{pl}$ for training (P=0.006) and time (P<0.001) but not for supplement (P=0.647, Figure 5-7). Each group was analysed separately to determine trends; no differences were detected at any time point for the CON group, however, in the EXP group post-hoc analysis indicated a significant increase in $[K^+]_{pl}$ post-training at several time points (Figure 5-7).

A significant difference was observed for training (P=0.047) and time (P<0.001) in $\Delta[K^+]_{pl}$ but not for supplement (P=0.632, Figure 5-8). Although $\Delta[K^+]_{pl}$ was greater during post-training, post-hoc testing could not locate where the specific differences occurred (P>0.078).

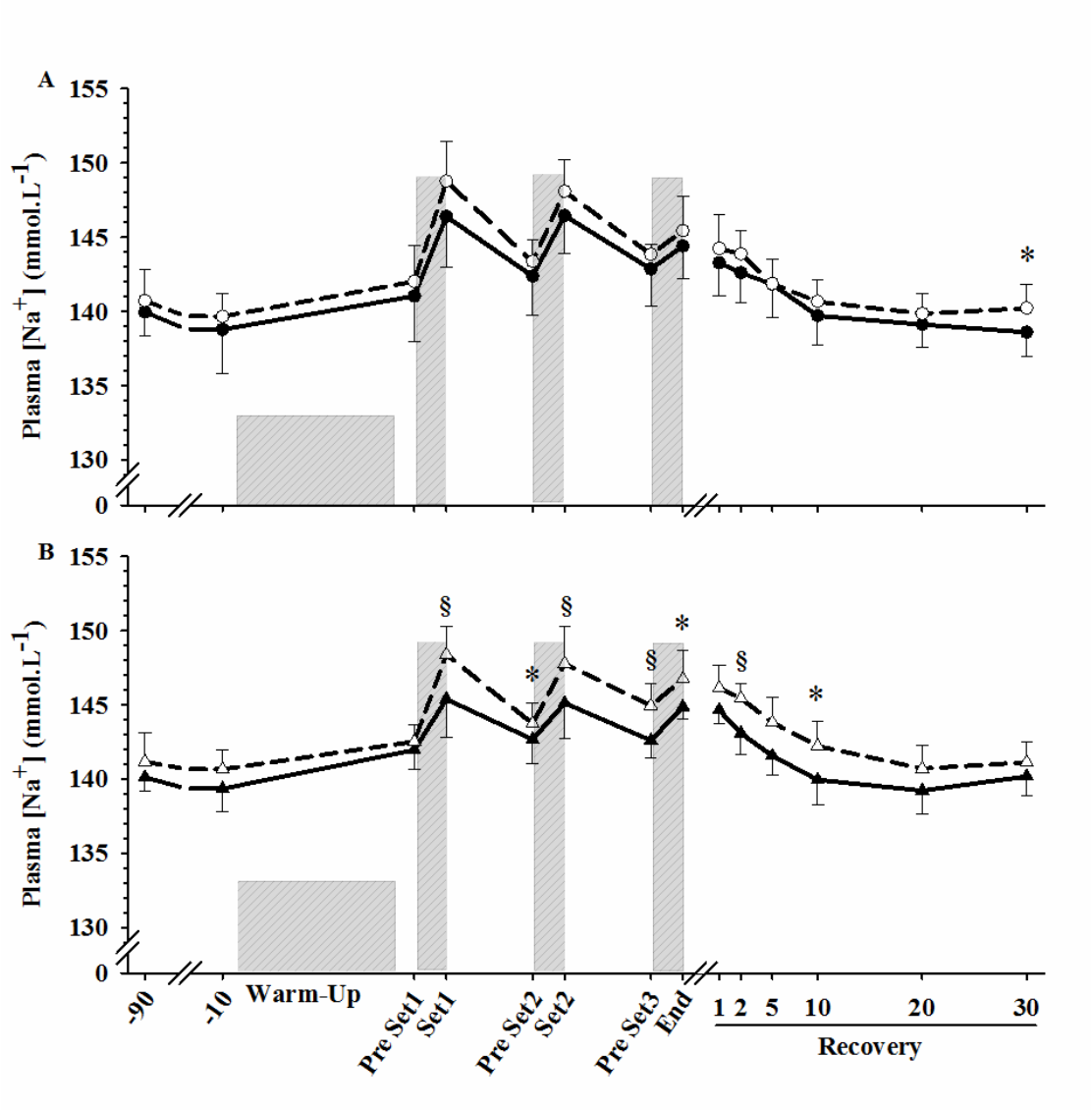

Figure 5-6Venous plasma [Na^+] during RSE and recovery during PRE (closed symbols) and POST (open symbols) testing for EXP (circles), (A) and CON (triangles), n=7 (B) groups. Data are mean ± SD. * = greater than pre-training (P<0.05), § = greater than pre-training (P<0.01). Both groups ingested $CaCO_3$ prior to exercise during PRE and POST testing. Shaded area indicates exercise

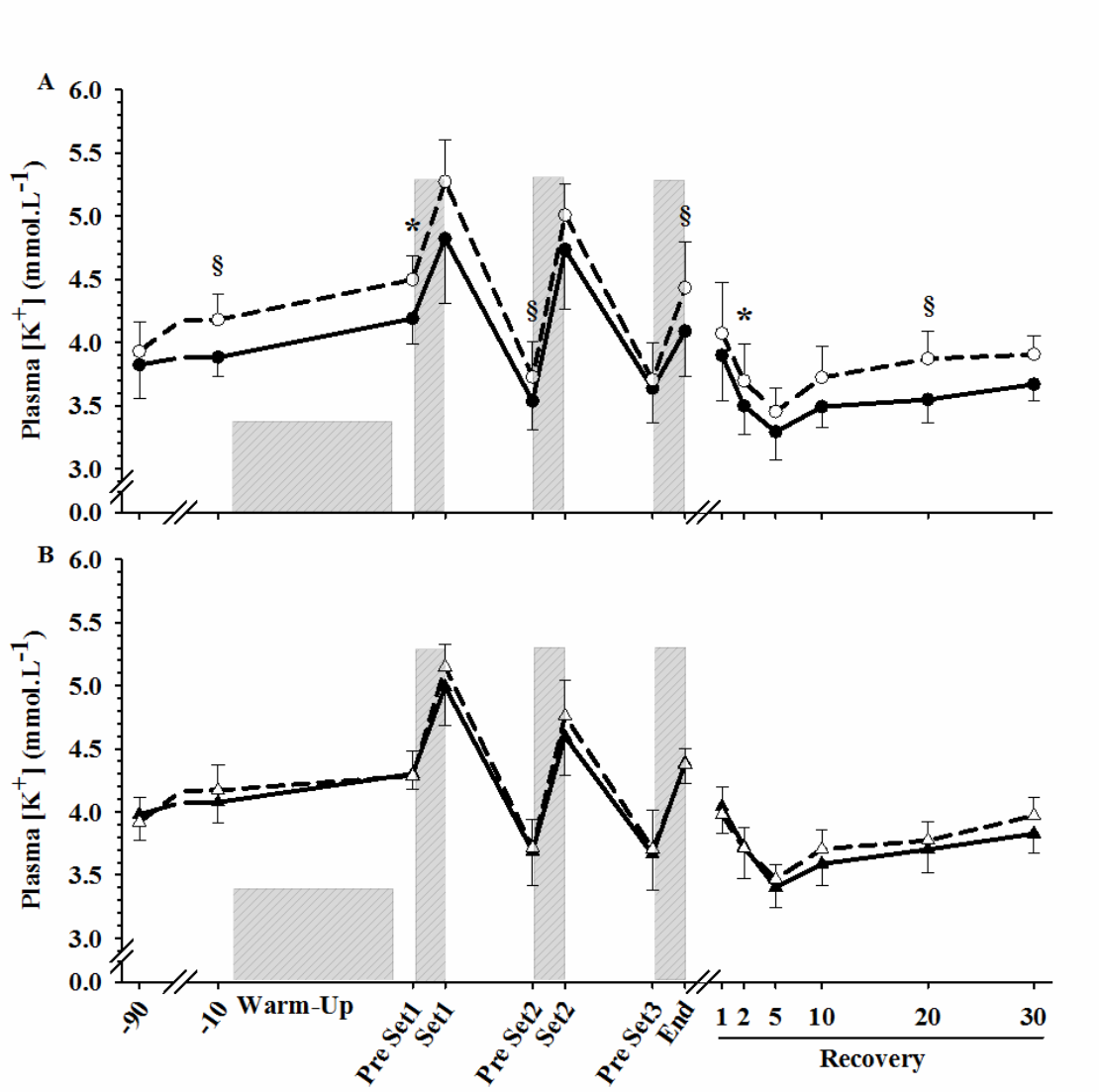

Figure 5-7 Venous plasma [K^+] during RSE and recovery during PRE (closed symbols) and POST (open symbols) testing for EXP (circles), (A) and CON (triangles), n=7 (B) groups. Data are mean ± SD. * = greater than pre-training (P<0.05), § = greater than pre-training (P<0.01). Both groups ingested $CaCO_3$ prior to exercise during PRE and POST testing. Shaded area indicates exercise

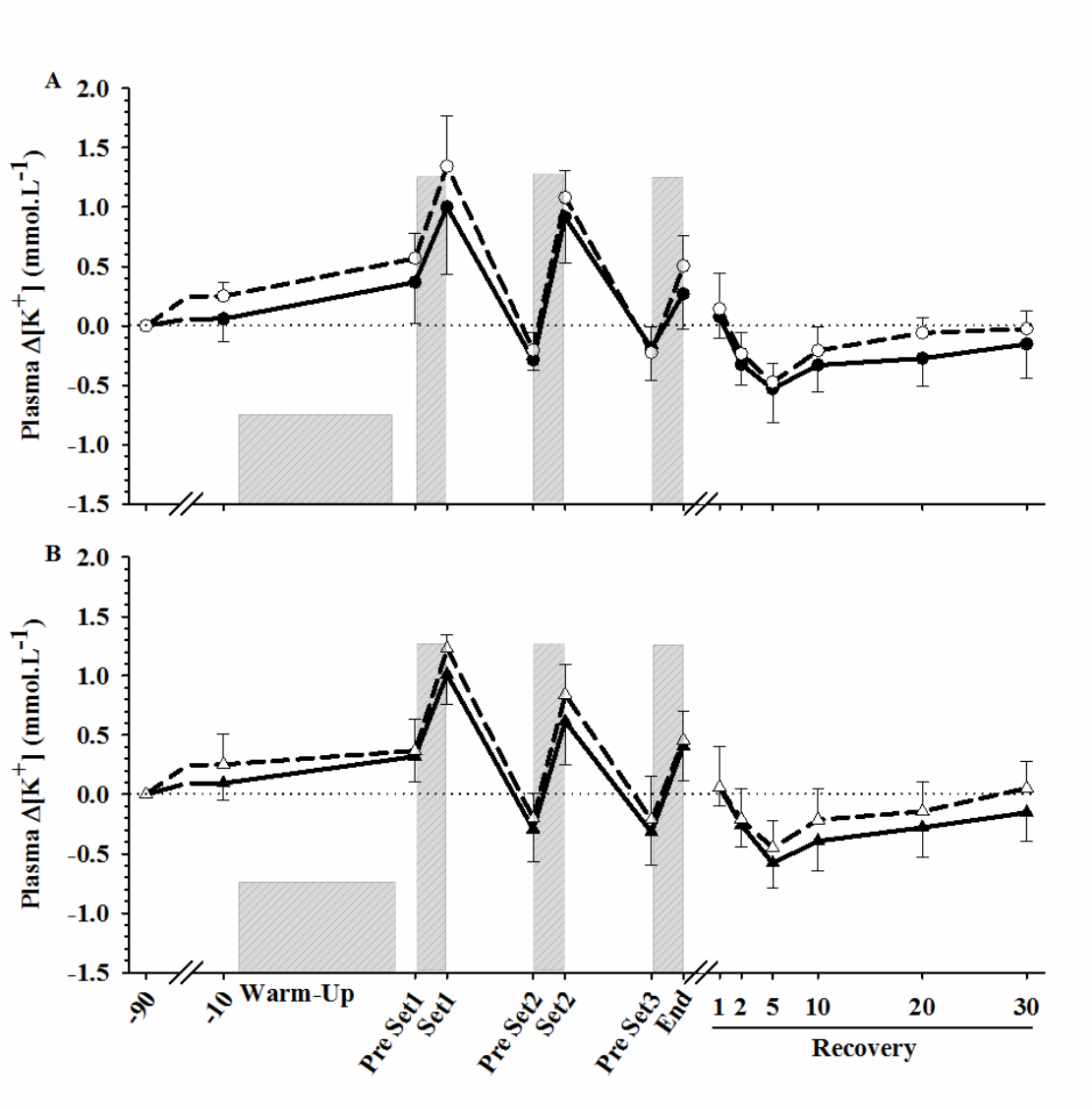

Figure 5-8 Plasma Δ[K⁺] during RSE and recovery during PRE (closed symbols) and POST (open symbols) testing for EXP (circles), (A) and CON (triangles), n=7 (B) groups. Data are mean ± SD. Both groups ingested $CaCO_3$ prior to exercise during PRE and POST testing. Shaded area indicates exercise

5.4 Discussion

The first main finding of this study was that although the acute ingestion of $NaHCO_3$ altered acid-base balance, acceleration and peak and mean speed did not improve during RSE following ingestion. Second, contrary to earlier reports, $NaHCO_3$ ingestion did not significantly lower $[K^+]_{pl}$ during exercise and recovery. Finally, four weeks of RST enhanced RSE performance, however, greater improvements did not occur when $NaHCO_3$ was ingested prior to each training session compared to placebo ingestion.

5.4.1 $NaHCO_3$ ingestion does not enhance repeat sprint exercise performance

Acute $NaHCO_3$ ingestion does not enhance performance during RSE involving maximal efforts of short duration, despite invoking significant changes in plasma pH, $[HCO_3^-]_{pl}$ and $[Na^+]_{pl}$ (Figure 5-2 and Figure 5-3). Specifically, the capacities to accelerate or reach a high speed were unchanged following $NaHCO_3$ ingestion. These results are in agreement with the only other study to assess peak and mean speed during RSE on a non-motorised treadmill, where performance was unaffected following $NaHCO_3$ ingestion (Gaitanos, et al., 1991). In the current study, RSE mean power was also unchanged after $NaHCO_3$ compared to placebo ingestion (ES; -0.07 – 0.06, data not shown). In contrast, a greater total work and power output during cycling RSE (5 x 6 s cycle sprints commencing every 30 s) has been observed following $NaHCO_3$ ingestion (Bishop, et al., 2004). In that study, sprint duration was 50% longer than those performed in this study, suggesting that extremely short duration efforts (4 s) may not be long enough for $NaHCO_3$ to influence performance. Short duration efforts may not provide sufficient time for substantial metabolic perturbations (such as a significant rise in $[K^+]_{pl}$) to occur. However, as blood was not sampled after each single effort, conclusions cannot be made and may be the premise for future research.

The ability to maintain acceleration or a high-speed across RSE sets was not enhanced with $NaHCO_3$ supplementation as evidenced by the similar between-set decrements for all performance measures in the ACUTE-EXP compared to the PRE-EXP trials. This provides strong evidence that the acute ingestion of $NaHCO_3$ does not attenuate fatigue during RSE involving efforts of extremely short duration. The mean power per set (Table 5-2), reduction

in pH of ~0.20 units and rise in lactate of ~8 mM during the RSE (Figure 5-2) all provide evidence of the high metabolic cost of the protocol. Therefore, the performance enhancing effects of $NaHCO_3$ may be more dependent on the exercise duration and the length of recovery periods than the extent of the physiological perturbations that occur during exercise.

5.4.2 Changes in plasma K^+ with repeat sprint exercise

The disturbances in $[K^+]_{pl}$ during RSE were relatively small, with the peak $[K^+]_{pl}$ being 4.82 ± 0.51 and 4.99 ± 0.30 mM after set 1 in the PRE trial for the EXP and CON groups respectively (Figure 5-3). These values are similar to the $[K^+]_{pl}$ values observed immediately after an intense period in the 1st (4.9 mM) and 2nd (4.8 mM) half of a soccer match (Krustrup et al., 2006b). A greater peak $[K^+]_{pl}$ of ~5.5 mM has been observed after the first 5 sprints of RSE (15 x 6 s sprints interspersed by 1 min recovery) (Mohr, et al., 2007) however, this may be due to resting $[K^+]_{pl}$ being ~0.5 mM higher than the resting values in the current study. Together these results support the use of RSE in replicating the changes in $[K^+]_{pl}$ that occur following intense periods of play in team sports.

5.4.3 $NaHCO_3$ ingestion did not lower plasma K^+ prior to or during repeat sprint exercise

The ingestion of $NaHCO_3$ did not lower $[K^+]_{pl}$ at rest prior to exercise (Figure 5-3). This may be due the time period over which $NaHCO_3$ was ingested and the length of time between initial ingestion and commencement of exercise. In agreement with the current study, others have reported $[K^+]_{pl}$ to be unchanged after 80 and 120 min when $NaHCO_3$ was ingested over a 30 and 60 min period respectively (Lindinger, et al., 1999; Stephens, et al., 2002). In contrast, $[K^+]_{pl}$ was significantly reduced at rest 90 min after the initial ingestion of $NaHCO_3$ compared to placebo ingestion (Raymer, et al., 2004), however, information about the time period in which $NaHCO_3$ was ingested was not provided. The ingestion of $NaHCO_3$ over a 15 min period lowered $[K^+]_{pl}$ 75 minutes after initial ingestion (Siegler, et al., 2010), suggesting a shorter ingestion period (e.g. 15 minutes rather than 60 mins) may elicit a faster K^+ response. However, the ingestion of $NaHCO_3$ in either a single dose or over a short period of time may increase the risk of gastrointestinal discomfort (Cameron et al., 2010). A similar ingestion

period to the current study resulted in a significant reduction in $[K^+]_{pl}$ 165 min after initial ingestion compared to pre-ingestion values (Lindinger, et al., 1999). This suggests that a longer period between supplement ingestion and exercise may have resulted in a reduction in $[K^+]_{pl}$. However, this would have decreased the practical application of the current study as the aim was to develop an intervention that could be used as a viable option for team sport athletes prior to training and or match performance. Further, it is unlikely that a longer ingestion time would have resulted in an improved RSE performance, as no differences were observed in peak speed, power or total distance covered during RSE (10 x 10 s sprints with 50 s recovery on a non-motorised treadmill) when $NaHCO_3$ was ingested at either 60, 120 or 180 min prior to exercise (Siegler, et al., 2012).

When the ingestion of $NaHCO_3$ has both lowered $[K^+]_{pl}$ and improved performance, the difference in $[K^+]_{pl}$ compared to placebo has been ~0.40 mM (Raymer, et al., 2004; Sostaric, et al., 2006). However, as a pre-ingestion blood sample was not taken during these studies, the $\Delta[K^+]_{pl}$ from pre-ingestion could not be determined. In the current study, there was a trend for $\Delta[K^+]_{pl}$ from pre-ingestion to be ~0.20 mM lower during all recovery periods following $NaHCO_3$ ingestion (Figure 5-3). This suggests that lowering $[K^+]_{pl}$ by a only small amount does not influence performance during this type of explosive short duration exercise, therefore it is possible that greater reductions in $[K^+]_{pl}$ may be required to enhance performance.

5.4.4 Repeat sprint training improves repeat sprint exercise performance both with and without $NaHCO_3$ supplementation

Four weeks of RST resulted in small-trivial improvements in acceleration and speed for both groups (Figure 5-4). The improvements by the EXP group in set 3 were of a smaller magnitude than the CON group (Table 5-2). As the CON group had greater decrements from set 1 to 3 in all performance measures prior to training compared to the EXP group, it is possible that they were more susceptible to fatigue during RSE at the commencement of training (Table 5-3). Therefore, larger improvements in performance with RST may occur in individuals with a poorer initial RSE performance. There were only trivial differences

between groups in the magnitude of improvement for peak and mean speed in set 1 and 2 (ES;-0.016 to 0.000, Table 5-2). Although the EXP group only experienced trivial improvements in peak and mean speed in set 1 whilst the CON group experienced small increases (Table 5-3), the trivial increases in the EXP group may be due to a greater variability in individual performance, as indicated by a larger standard deviation (Table 5-2). Interestingly, despite both groups experiencing small improvements in acceleration only the CON group had an increase in mean power following RST (Figure 5-4). This is surprising as power has been suggested to be an important determinant of acceleration capacity (Cometti, et al., 2001; Lockie, et al., 2010). The improvement in acceleration yet absence of change in mean power experienced by the EXP group suggests that the improvements in acceleration may be related to other factors that can increase acceleration such as neural adaptations including improvements in intramuscular coordination or an increase in step frequency (Kristensen, van den Tillaar, & Ettema, 2006; Lockie et al., 2012). In the current study, given the similarity in mean power between groups at baseline, it appears the lack of improvement in mean power may be due to the supplementation of $NaHCO_3$, however the mechanisms for this are unclear given the similar group changes in acceleration. Future research should investigate the effects of chronic $NaHCO_3$ supplementation on training specifically designed to improve peak and/or mean power. Since chronic $NaHCO_3$ ingestion did not improve any performance measures to a greater extent than the placebo group following RST and was actually associated with no change in mean power its use is not recommended during RST involving explosive short duration efforts.

5.4.5 Repeat sprint training does not enhance K^+ regulation both with and without chronic $NaHCO_3$ supplementation

This is the first study to report the physiological adaptations to RST when combined with $NaHCO_3$ ingestion prior to each training session. A main effect for training indicated an increase in $[K^+]_{pl}$ and Δ $[K^+]_{pl}$ in both groups post-training, however, with the exception of $[K^+]_{pl}$ in the EXP group post-hoc analysis could not detect where the specific differences occurred (Figure 5-7and Figure 5-8). These increases are in contrast to the only other study to

investigate changes in K^+ regulation following short duration RST. After eight weeks of RST (15 x 6 s sprints interspersed by 1 min recovery) there was no difference in $[K^+]_{pl}$ throughout the RST protocol, between the first and last training session, despite a 6% increase in total work (total distance covered) (Mohr, et al., 2007). As the accumulation of plasma K^+ is greater at higher intensities (Medbø & Sejersted, 1990), an unchanged $[K^+]_{pl}$ at a greater work rate represents an improvement in K^+ regulation possibly due to increased Na^+,K^+-ATPase activity (Mohr, et al., 2007). In the current study, $[K^+]_{pl}$ and $\Delta[K^+]_{pl}$ were significantly greater in both groups following RST, suggesting K^+ regulation had not been improved. The training period in the current study was much shorter than that of the aforementioned RST study (12 vs. 32 total training sessions, respectively) as was the duration of each maximal effort (4 vs. 6 s, respectively) (Mohr, et al., 2007). Therefore it is possible that the type of training used in this study was not sufficient to stimulate the physiological adaptations that would improve the regulation of K^+, such as an increase in Na^+,K^+-ATPase activity (Mohr, et al., 2007). This is supported by research from this laboratory that has found no change in the level of Na^+,K^+-ATPase $\alpha1$, $\alpha2$ and $\beta1$-isoforms following this type of RST (Serpiello, McKenna, Bishop, Aughey & Stepto, unpublished data).

The lack of improvement in K^+ regulation, in the current study, suggests that the greater $\Delta[K^+]_{pl}$ in the CON group post-training was due to the greater mean power performed per set (Figure 5-3). However, it is unclear as to why the EXP group also experienced a greater $\Delta[K^+]_{pl}$ post-training as mean power was unchanged (Figure 5-4). It is possible that the chronic supplementation of $NaHCO_3$ during RSE may have blunted several physiological adaptations occurring in response to RST by acutely altering the physiological disturbances during RSE. However as transport proteins were not measured in this study, it is difficult to make any inferences on the different training induced adaptations that may have occurred.

The contrasting changes between groups in mean power following RST may also explain why plasma pH was lower during exercise and recovery in the CON group post-training (Figure 5-5), yet unchanged in the EXP group. Following seven weeks of intermittent all-out exercise training (4-10 x 30 s cycle sprints interspersed by 3-4 min recovery), the increase in $[H^+]_{pl}$

was greater during an all-out sprint test to exhaustion, however a lower rise in $[H^+]_{pl}$ was observed when the test was matched to the work performed pre-training (Harmer, et al., 2000). The magnitude of H^+ accumulation is associated with the amount of work performed and would explain the increase in plasma pH (Figure 5-5) with an increase in mean power (Figure 5-4) in the CON group and the similar plasma pH (Figure 5-5) with an unchanged mean power (Figure 5-4) in the EXP group following RST.

Interestingly, despite a greater $\Delta[K^+]_{pl}$ post-training, both groups had improvements in peak and mean speed and acceleration. This suggests that the disturbances in $[K^+]_{pl}$ that occur with repeated short duration maximal efforts common to team sports are not large enough to inhibit the performance of these efforts. Within the context of team sport, high-intensity maximal efforts are performed intermittently amongst running periods of varying intensities (See Chapter 4), which were not present during the RSE protocol in the current study. Due to the large between-match variability in high-speed running, a typical CV of ~17% (Gregson, et al., 2010), it is likely that the high metabolic perturbations during intense period of play will differ between games and individuals. It is unclear if a greater rise in $[K^+]_{pl}$ may affect RSE performance, therefore future research should investigate the K^+ response during RSE using protocols which include intermittent running at a variety of intensities.

There were several limitations to this study. First, the assessment of the effects of $NaHCO_3$ on $[K^+]_{pl}$ and RSE performance were not run in a counterbalanced manner, further, the data from the CON group during the ACUTE trial were not collected. Therefore, any learning effects from multiple RSE sessions or negative effects of $NaHCO_3$ on RSE performance were unable to be unaccounted for. However, as there was no change in RSE performance these effects are unlikely. An additional familiarisation trial may have reduced any learning effects present and is recommended for future research. Second, the CON and EXP groups were unable to be matched based on both RSE acceleration and peak speed performance at baseline. This was due to the large variability between individuals in RSE performance, rendering it difficult to match both performance measures.

In conclusion, the acute ingestion of $NaHCO_3$ does not enhance performance during RSE. Furthermore, 4 weeks of RST can elicit small changes in acceleration and speed without improvements in K^+ regulation. Therefore, whilst the use of RST is recommended as a training tool for developing acceleration and speed in team sports athletes, the concomitant ingestion of $NaHCO_3$ will not lead to greater improvements in performance.

CHAPTER 6. GENERAL DISCUSSION AND CONCLUSIONS

6.1 General discussion

6.1.1 Introduction

The information presented in this thesis provides an insight into the role of accelerations in soccer by profiling their occurrence during competition and assessing the efficacy of two interventions to enhance their performance. The first study determined if the rapid changes in speed that occur during acceleration and high-speed movements could be accurately measured with GPS technology by assessing the validity and reliability of this system for measuring instantaneous speed. Using this information, a second study was conducted to quantify the high-intensity movements undertaken by elite Australian soccer players during competition, specifically profiling acceleration patterns. The final study, investigated the efficacy of two interventions (training and supplementation) to enhance the capacity to accelerate both separately and in combination. In this section, the major findings from these studies will be consolidated and discussed in reference to the related literature and research that has been published following the completion of this work.

6.1.2 Validity and reliability of GPS for measuring instantaneous changes in speed

Before accelerations could be quantified during match-play, it was important to determine a tool that could provide an acceptable level of measurement for detecting these movements. Prior to this thesis the validation of GPS devices for measuring speed had only conducted by assessing average or peak speed (Coutts & Duffield, 2010; Duffield, et al., 2010; MacLeod, et al., 2009). Therefore, in study one (see Chapter 3) the validity and reliability of 5 and 10 Hz GPS (MinimaxX v2.0 and v4.0 respectively) for measuring instantaneous speed during the acceleration, constant speed and deceleration phases of straight-line running were assessed. The main finding was that the validity and the reliability of GPS for measuring instantaneous speed across all running phases were improved with a higher sampling frequency (Table 3-1and Table 3-2). These results are in agreement with other validation studies where GPS

measures of distance and average speed were more accurate and reliable in GPS sampling at 5 Hz compared to 1 Hz (Duffield, et al., 2010; Jennings, et al., 2010a).

Although more recent GPS validation studies have been conducted, they have only evaluated 5 Hz devices (Johnston et al., 2012; Waldron, et al., 2011), as such, the comparison of different GPS brands and/or models has not been further explored. One study has assessed the ability of 5 Hz GPS (MinimaxX V2.5) to accurately detect instantaneous peak speed during a flying 50 m sprint by comparing GPS speed to speed measured by a radar gun sampling at 31 Hz (Johnston, et al., 2012). However, the 5 Hz GPS measure of instantaneous peak speed was only moderately correlated with the measure from the radar gun (Pearson's correlation coefficient (*r*) of 0.36 to 0.46). In study one, the closest measure to peak speed was constant speed running at 5 – 8 $m.s^{-1}$, where only a small correlation (r =0.28) was observed between 5 Hz GPS and the criterion measure. While this provides an opportunity to indirectly compare measures of instantaneous speed between 5 Hz MinimaxX GPS with different chipsets (V2.5 and V2.0), it is difficult to make any inferences on this data as the grouping of running speeds in study one is not a true reflection of peak speed.

Study one of this thesis identified two important considerations that should be accounted for if GPS are to be used to quantify acceleration and high-speed efforts. First, regardless of the sample rate, the accuracy and reliability of GPS for measuring instantaneous speed is reduced with an increase in the rate of change in speed (Table 3-1 and Table 3-2). Second, instantaneous speed is underestimated when the rate of change in speed is high. Similar measurement issues are commonly observed in other GPS validation studies. For example, the accuracy and reliability of 1, 5 and 10 Hz GPS measures of distance and/or average speed are reduced when the movement task assessed involves an accelerative component (e.g. commencement from a stationary start) or when the distance of the movement is reduced (e.g. 20 m vs. 40 m Sprint), resulting in a greater variation in the change of speed (Castellano, et al., 2011; Jennings, et al., 2010a; Petersen, et al., 2009). Further, a number of studies have reported 1, 5 and 10 Hz GPS to underestimate distance during short high-speed efforts

compared to the criterion measure (Castellano, et al., 2011; Duffield, et al., 2010; Gray, et al., 2010; Jennings, et al., 2010a; Waldron, et al., 2011).

A limitation for study two, due to the use of soccer players from elite Australian clubs was the brand and model of GPS units used by the participating clubs. Not only were the units a different brand to that used in study one (GPSports vs. MinimaxX) but they also operated at the lower sample rate of 5 Hz. The validation of both brands of 5 Hz GPS units used in study one and two (MinimaxX V2.0 and GPSports SPI-Pro, respectively) for measuring distance covered during 20, 30 and 40 m sprint efforts, found the GPSports units to have a smaller standard error of the estimate, percentage bias and better reliability than the MinimaxX units (Petersen, et al., 2009). As the sprints were undertaken from a stationary start, these results suggest the validity and reliability of the GPSports units used in study two were superior for assessing rapid changes in speed than the MinimaxX units used in study one. Based on the findings of study one, several modifications to the analysis of GPS data in study two were made to account for the measurement error associated with 5 Hz GPS and increase the ecological validity and reliability of detecting acceleration and high-speed efforts.. First, a minimum of two consecutive samples above the desired speed threshold were required for an effort to be considered real and not a product of the noise associated with 5 Hz GPS (Aughey, 2011b). Second, only the occurrences of acceleration, sprint and high-speed efforts were reported as opposed to the individual effort distances and durations.

6.1.3 Performance of acceleration and high-speed efforts during competition in elite Australian soccer players

A large amount of soccer-based research has focused on describing the high-intensity movements performed in soccer. Typically this involves reporting the occurrence and/or total distance of sprint and/or high-speed running efforts throughout a game (Table 2-2 and Table 2-3), or of peak periods of high-speed running (Bradley, et al., 2009b; Mohr, Krustrup, & Bangsbo, 2003). However, only a limited number of studies have included a measure of acceleration in their analysis (Bradley, et al., 2009a; Osgnach, et al., 2010). The findings of study two (see Chapter 4) show that soccer players undertake an ~8-fold greater number of

maximal acceleration compared to sprint efforts during competition and that the majority of these accelerations are performed from low speeds that do not exceed the high-speed threshold. Despite the importance that has been placed on the ability to undertake sprint efforts during competition (Di Salvo, et al., 2010), sprint occurrence was surpassed by maximal accelerations at a ratio of 8:1. As a high energy-expenditure is required to accelerate (Osgnach, et al., 2010), the research undertaken in study two highlights the necessity of including measurements of maximal acceleration in soccer match analysis.

The inclusion of accelerations in match analysis will allow researchers to further understand the role these efforts play in soccer, specifically, the relationship between in-game acceleration performance and match actions. The premise of this research is that accelerations are vital during critical match activities, such as being first to the ball or moving past an opponent (Carling, et al., 2008). However, this is based on anecdotal evidence and is yet to be supported by research. The integration and synchronisation of match footage and GPS data would allow researchers to assess the occurrence of high-intensity activities, such as accelerations, during specific match actions. While this is possible with match analysis systems that incorporate video (see sections 2.1.4 and 2.1.6), limited research has been conducted linking individual efforts to specific match outcomes (Faude, Koch, & Meyer, 2012). This is likely due to the time-consuming nature of such a task and the methodological issues discussed in sections 2.1.6 and 2.1.7. Such research would add credence to the claims that accelerations are important to decisive match activities.

The relationship between acceleration performance and match outcome, for example, winning, drawing or losing a match is also important for practitioners to consider. Mediating variables such as playing position, match experience and match outcome may provide some clarity on the role accelerations play during a match. This has been investigated in Australian football, where the relationship between physical capacity and number of ball disposals was mediated by player position, experience and high-speed running distance (Mooney et al., 2011). A similar method could be used to explore the relationship between acceleration performance and a range of measures, such as, match outcome or physical capacity.

6.1.4 Effectiveness of repeat sprint training with and without $NaHCO_3$ ingestion to enhance acceleration performance during repeat sprint exercise

The findings from study two, that soccer players undertake far more acceleration than sprint efforts during competition, suggests that training to enhance the capacity to rapidly accelerate may be just as important as the capacity to reach high-speeds. While RST can improve acceleration performance (Serpiello, et al., 2011), the potential for greater enhancements in performance via the concomitant supplementation of an ergogenic aid would be of interest to conditioning staff. Thus, study three investigated the effectiveness of RST and $NaHCO_3$ supplementation for improving the capacity to accelerate. Four weeks of RST improved acceleration performance during RSE, however the additional ingestion of $NaHCO_3$ before each training session did not result in greater improvements compared to placebo ingestion. Further, the acute ingestion of $NaHCO_3$ prior to RSE did not improve acceleration performance during exercise.

The ingestion of $NaHCO_3$ was also expected to lower $[K^+]_{pl}$ prior to exercise and attenuate it's increase during exercise (Sostaric, et al., 2006), thus reducing muscular fatigue and allowing a greater preservation of acceleration performance throughout exercise. However, $[K^+]_{pl}$ was unchanged following $NaHCO_3$ ingestion, possibly due to an insufficient length of time between ingestion and exercise, as discussed in Chapter 5. Although $NaHCO_3$ ingestion did not attenuate the increase in $[K^+]_{pl}$ during RSE, it is unknown if $NaHCO_3$ ingestion would have been more influential should the perturbations in $[K^+]_{pl}$ during exercise been higher. In study three, the peak K^+_{pl} during RSE was similar to $[K^+]_{pl}$ observed following intense periods of the 1st and 2nd half of a soccer match (Krustrup, et al., 2006b). However, in that study, information regarding the identification and selection of an intense period were not provided. Peak periods of activity during match-play may be underestimated depending on the analysis technique used (Varley, Elias, & Aughey, 2012). Further, given the large between-match variability in high-speed running distance (Gregson, et al., 2010) it is possible that some players may experience higher $[K^+]_{pl}$ during match-play than what has been reported. The RSE protocol in study three involved passive recovery periods that would be much longer

than those experienced during a soccer match. Thus, researchers should investigate the effects of $NaHCO_3$ ingestion on $[K^+]_{pl}$ and performance on the non-motorised treadmill using specific team sport protocols which involve a variety of movements at different speeds similar to those undertaken during competition (Sirotic & Coutts, 2008).

While acceleration performance was improved following four weeks of RST, it is unclear how these improvements in physical capacity may affect physical performance during competition. It could be speculated that players may experience an increase in the number of accelerations performed and/or an increase in the rate of these accelerations. However, physical capacity is not necessarily related to in-game physical performance, as performance may be limited by the positional role of the player or the tactics employed (Mendez-Villanueva, et al., 2011b). Therefore, the efficacy of a training intervention should be assessed in relation to both physical capacity and in-game performance. This can be achieved by investigating both changes in an individual's match activity profile and performance testing before and after a training intervention. Identifying whether the changes in match physical performance are due to the training intervention or a product of match-to-match variability may be difficult. Therefore, investigation into the between-match variability of acceleration occurrence is also required. As activity in matches may be highly variable (Gregson, et al., 2010) firm conclusions in relation to the effects of a training intervention can only be drawn if a substantial number of matches are observed.

6.2 Practical application

The practical applications of this thesis are:

1. Practitioners are recommended to use 10 Hz GPS units where applicable when tracking the movements of team sport athletes.
2. If the use of 5 Hz GPS is unavoidable, the level of error should be considered when interpreting the data. For example, only reporting the occurrence of these high-intensity efforts rather than detailed information such as individual effort distance or duration.

3. The measurement of movements where the rate of change in speed is high are likely to be underestimated by GPS regardless of sampling frequency and therefore represent the minimum of what is actually undertaken.
4. Match analysis research should include measures of acceleration when describing the high-intensity movements undertaken during soccer.
5. The ingestion of $NaHCO_3$ is not recommended to improve acceleration and speed performance during repeated short duration (< 6 sec) maximal exercise.
6. Repeat sprint training can be used to improve acceleration and speed performance during repeated short duration (< 6 sec) maximal exercise.

6.3 Conclusions

The specific conclusions of this thesis are:

1. The 10 Hz GPS units are more accurate and reliable than 5 Hz units for detecting changes in speed.
2. The accuracy of 5 and 10 Hz GPS units is negatively affected by a high rate of change in speed.
3. Both 5 and 10 Hz GPS units underestimate speed during accelerative and high-speed movements.
4. The accuracy of 5 and 10 Hz GPS units for measuring changes in speed when decelerating is poor.
5. Elite Australian soccer players perform an ~8-fold greater number of maximal accelerations than sprint efforts per game.
6. Of maximal accelerations ~98% commence from a starting speed lower than what would be considered high-speed running, while 85% do not cross the high-speed running threshold.
7. The ingestion of $NaHCO_3$ before RSE does not improve acceleration or peak speed performance during exercise.
8. The ingestion of $NaHCO_3$ before RSE does not alter the plasma K^+ response during or following exercise.

9. Four weeks of RST can improve acceleration and speed performance during RSE.
10. The ingestion of $NaHCO_3$ prior to each training session during four weeks of RST does not further enhance the improvements in acceleration or speed.

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APPENDIX A. INFORMATION FOR PARTICIPANTS

A.1 Study one - Information for participants for study one

VICTORIA UNIVERSITY | A NEW SCHOOL OF THOUGHT

INFORMATION TO PARTICIPANTS INVOLVED IN RESEARCH

You are invited to participate

You are invited to participate in a research project entitled

"Validity and reliability of a 5 Hz Global Positioning System for measuring accelerations in team sports"

This project is being conducted by a student researcher, Matthew Varley as part of a PhD study at Victoria University under the supervision of Dr Robert Aughey from the School of Sport and Exercise Science.

Project explanation

The analysis of movement demands in team sports allows sports scientists and coaches to evaluate performance which can assist in designing and improving specific training programs. While most research has focused on high-velocity movements, it is important to realise that acceleration, defined as the rate of change of velocity, is a high-intensity activity even though it does not always occur from a high-velocity. Acceleration is a key match attribute as it allows players to move past an opponent, be first to the ball and create and stop goal scoring opportunities. To date there is no validated method for the measurement of acceleration over short distances.

The introduction of new technology such as Global Positioning System (GPS) allows for an efficient way of collecting match data from a large sample size and is commonly used in Australian rules football, rugby and soccer. Although there have been several studies looking at the validity of GPS for measuring distance and velocity, the majority of these studies have used 1 Hz GPS. Recently 5 Hz GPS have become commercially available although currently there is only a single study looking at validity.

This study is intended to determine the validity and reliability of a 5 Hz GPS for measuring acceleration in team sports. If successfully validated this will open up many areas for further research and allow for the quantification of high-intensity activity, including acceleration data, performed during a match.

What will I be asked to do?

Participants will be asked to perform a linear acceleration trial set up over 30 m wearing 3 GPS units operating at 5 Hz at a range of velocities from 1 – 8 $m.s^{-1}$.

What will I gain from participating?

Participants will be taking part in an invaluable study adding much needed research to the area of motion analysis in team sports. This has the potential to improve the way performance in team sports is monitored. The study also allows the participant the opportunity to experience using a 5 Hz GPS which has a recommended retail price of approximately $4000.

How will the information I give be used?

GPS velocity data will be compared with velocity data determined by a laser measurement device and radar gun to determine the validity of GPS for measuring acceleration in team sports. GPS velocity data will be compared between units and typical error determined to evaluate reliability of GPS for measuring acceleration in team sports. Data collected will be coded by the GPS unit worn allowing participants' identity to remain protected. Access to the data is restricted to only the two researchers. Data will be stored for 5 years as set by university regulations.

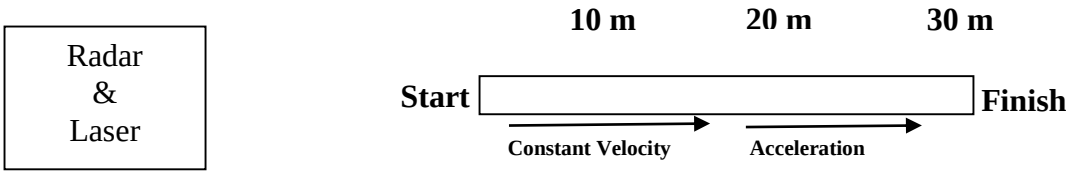
What are the potential risks of participating in this project?

During the linear acceleration trial there is the unlikely risk of sudden death due to myocardial infarction or vasovagal episode. This risk will be reduced, as the participant is required to fill out a Risk Factor Assessment Questionnaire before being accepted for the study. There is also a risk of muscle soreness and overuse injury due to the number of bouts required and the velocity at which the participant must reach. This will be minimised by spreading the trials out over a 1 week period. During the trials players will be exposed to a Class 1 laser, which under European Standards is not harmful to the human eye. As a precautionary measure the laser will be focused at the participants back to minimise eye contact.

How will this project be conducted?

Participants will be required to run through the linear acceleration trial which will be indicated by a marked line over 30 m (Fig 1). Participants will wear an earpiece attached to a walkie talkie worn around the waist during each trial. An audio cue will be played continuously during each trial to indicate the required pacing. A constant velocity will be established over the first 20 m in 1 $m.s^{-1}$ velocity bands from 1 – 8 $m.s^{-1}$. Upon reaching the 20 m mark the participant will be required to perform either a mild, moderate or maximal acceleration all the way through to the finish.

FIGURE 1: *Linear Acceleration Trial*



Participants will be required to perform 10 bouts at a range of constant velocities and accelerations, totalling 120 bouts. During each bout participants will wear 3 GPS units placed securely in a custom made vest that positions the unit on the posterior side of the body between the shoulder blades. Velocity and distance will be recorded during each trial by a laser and radar supported on a tripod 15m before the start line. GPS velocity data will be compared with laser/radar data to determine validity. GPS velocity data will be compared between simultaneously worn units to determine reliability.

Who is conducting the study?

This study is being conducted by Victoria University, Faculty of Arts, Education and Human Development, School of Sport and Exercise Science.
If you become stressed as a result of your participation please feel free to consult Dr Harriet Speed a registered psychologist free of charge on (03) 99195412 or at harriet.speed@vu.edu.au

For further information regarding this study please contact the Principal Researcher, Dr Robert Aughey, ph, 9919 5551, mobile 0448 153 597; email robert.aughey@vu.edu.au or Student Researcher, Matthew Varley, ph, 9919 4207, mobile 0419 628 451; email matthew.varley@live.vu.edu.au

Any queries about your participation in this project may be directed to the Principal Researcher listed above.

If you have any queries or complaints about the way you have been treated, you may contact the Ethics and Biosafety Coordinator, Victoria University Human Research Ethics Committee, Victoria University, PO Box 14428, Melbourne, VIC, 8001 phone (03) 9919 4148.

A.2 Study two - Information for participants

INFORMATION TO PARTICIPANTS INVOLVED IN RESEARCH

You are invited to participate

You are invited to participate in a research project entitled
"Acceleration and fatigue in elite soccer: An in-depth analysis of high-intensity activity"

This project is being conducted by a student researcher, Matthew Varley as part of a PhD study at Victoria University under the supervision of Dr Robert Aughey from the School of Sport and Exercise Science.

Project explanation

The analysis of the player movement demands in soccer can provide information which allows sports scientists and coaches to shape conditioning and improve the specificity of training. Although player only spends approximately 8.7% of the match performing high intensity activities, such as high-velocity running and sprinting, it is these movements which play a key part in the outcome of a match. Acceleration, the rate at which changes in velocity occur, can allow a player to be first to the ball, get past an opponent and move into space. While previous studies have looked at the high-velocity running profiles of players during a match there is little information on acceleration.
Previously video based time-motion analysis has been used to determine movement patterns in soccer although this method is found to be quite labor intensive. The introduction of new technology such as Global Positioning Systems (GPS) allows for much more efficient way to track players and can provide information on changes in velocity, distance covered as well as frequency and duration spent at different velocities.
This study is intended to investigate the high-intensity activity profiles of players during a match. This includes information on the duration, frequency and distance of acceleration and high-velocity running efforts during a match as well as the commencement speed of accelerations, recovery time between efforts and the positional differences in the aforementioned parameters. The information collected will provide an in-depth understanding of the physically demanding tasks undertaken by elite A-League soccer players. This can assist in the way fitness training is designed and implemented in an effort to enhance performance.

What will I be asked to do?

The project does not require you to do any additional work to that which you already undertake during a match. You will be asked to give your written consent for the researcher to access the GPS game files that are collected on match day. Your involvement in this study is completely voluntary and you are under no obligation to participate if you do not wish to do so. Furthermore you may withdraw from the study at anytime.

What will I gain from participating?

Your participation in this project will provide you with detailed feedback relating to your performance during a match. This information will be unique to Melbourne Victory and allow coaching staff to assist your development.

How will the information I give be used?

The information obtained during this project will be used to examine and describe the high-intensity activity demands of elite A-League soccer players.

What are the potential risks of participating in this project?

Players may be concerned or stressed that the data collected is used to analyse their performance. However, this would be the case regardless of the additional data being collected here.

All data that is published will hide the names of the individual participants. Instead the results will be shown by position so that your identity will remain protected. Access to the data is restricted to only the two researchers as well as Anita Pedrana. Data will be stored for 5 year as set by University regulations. Furthermore participation in this study is completely voluntary and the decision to not participate will not influence team selection.

If you become stressed as a result of your participation please feel free to consult Dr Harriet Speed a registered psychologist free of charge on (03) 99195412 or at harriet.speed@vu.edu.au

How will this project be conducted?

Using GPS data collected during matches, the researcher will perform a detailed analysis of the high-intensity activity demands during match play. This will be conducted using a custom-made excel spreadsheet.

Who is conducting the study?

This study is being conducted by Victoria University, Faculty of Arts, Education and Human Development, School of Sport and Exercise Science.

For further information regarding this study please contact the Principal Researcher, Dr Robert Aughey, ph, 9919 5551, mobile 0448 153 597; email robert.aughey@vu.edu.au or Student Researcher, Matthew Varley, ph, 9919 4207, mobile 0419 628 451; email matthew.varley@live.vu.edu.au

Any queries about your participation in this project may be directed to the Principal Researcher listed above.

If you have any queries or complaints about the way you have been treated, you may contact the Ethics and Biosafety Coordinator, Victoria University Human Research Ethics Committee, Victoria University, PO Box 14428, Melbourne, VIC, 8001 phone (03) 9919 4148.

A.3 Study three - Information for participants

INFORMATION TO PARTICIPANTS INVOLVED IN RESEARCH

You are invited to participate

You are invited to participate in a research project entitled
"The effects of sodium bicarbonate ingestion on ionic regulation and performance during repeated-sprint exercise training"

This project is being conducted by a student researcher, Matthew Varley as part of a PhD study at Victoria University under the supervision of Dr Robert Aughey, Professor Michael McKenna and Dr. Nigel Stepto from the School of Sport and Exercise Science.

Project explanation

The ability to repeatedly perform short bouts of high intensity exercise is an important component of intermittent team sports. Acceleration in particular is a key match activity as it allows players to move past an opponent, be first to the ball and create and stop goal scoring opportunities. Muscle fatigue may hinder the ability to repeatedly perform such high-intensity activities during team sports with players performing less high-intensity running both towards the end of a match and after periods of increased high-intensity movement. It has been suggested that an accumulation of electrolytes (specifically potassium outside the muscle cell) may contribute to this fatigue during intense exercise.
Sodium bicarbonate ($NaHCO_3$) supplementation can improve exercise performance (Increased total work) when taken prior to acute exercise. Similarly high-intensity training can lead to an increased performance (Increased Yo-Yo Intermittent Recovery Test performance, an aerobic performance test specifically used to assess an individual's ability to repeatedly perform high-intensity exercise). Both interventions have been suggested to lower the accumulation of potassium outside the muscle cell during exercise. However there is no literature available that has looked at the effects of high-intensity training in combination with $NaHCO_3$ supplementation.
This project looks to investigate the effects of 4-weeks of repeat-sprint training combined with $NaHCO_3$ supplementation on exercise performance and ionic regulation.

What will I be asked to do?

You will be asked to fill in several short questionnaires about your family medical history and your exercise habits. Participants will be selected for the study based upon this questionnaire data, those not selected will have this data destroyed. Participants who are selected will be asked to attend the Exercise Physiology Laboratory at Victoria University Footscray Park on 20 occasions; six testing sessions before training, a 4-week period of training (3 sessions per week) and two additional testing sessions after training. Prior to three testing sessions and each training session, you will be given either an experimental substance ($NaHCO_3$) or a placebo substance ($CaCO_3$). You will be asked for your permission for a medical doctor to perform a muscle biopsy (collection of a small sample of your muscle (the equivalent of 3-4 rice grains) using a biopsy needle) once before training and twice after, on three occasions – twice before and once after training. You will be also asked for your permission for a medical doctor to perform a venous cannulation (insertion of a small tube into the vein of the forearm via a needle) allowing venous blood samples to be taken during four sessions.

What will I gain from participating?

From participation in the study you can expect to gain strong benefits to your aerobic fitness as well as increasing your knowledge of fitness and fitness testing. Undertaking the repeat-sprint protocol you can expect to gain improvements in your ability to accelerate and perform repeated-bouts of high-intensity activity. Additionally you will receive $200 for full completion of the study for which the terms are outlined below:
Participants will be required to attend the Exercise Physiology Laboratory at Victoria University Footscray Park Campus on 20 occasions; 5 visits (familiarization and baseline testing), 1 visit (pre-testing and acute exercise) and 14 visits (training and post-testing). Each trial will last approximately 1.5 hours except the double baseline, pre-training and post-training trials which will last 4 hours each. Participants will receive approximately $10 reimbursement per visit. Reimbursement will cover the cost of public transport and time spent in the Exercise Physiology Laboratory.
Participants will be reimbursed according to their participation, allowing them to receive payment if they decide to withdraw or drop-out of the study prior to completion. The following payments will be made dependent upon involvement:

0% or $0 if they withdraw following the pre-testing ($\dot{V}O_{2peak}$ test, Yo-Yo IR1 test and familiarization) as these tests carry a commercial value of $200 - $300 at Victoria University and are deemed sufficient value not to require an honorarium.

20% or $40 upon completion of double baseline testing due to time commitments involved

60% or $120 upon completion of double baseline testing and 4 weeks of training due to time commitments involved

100% or $200 upon completion of the whole study

How will the information I give be used?

Blood and muscle samples will be stored under alphanumeric codes (i.e. without your name or personal details) and only the researchers will be able to connect the samples to you. All of the muscle samples collected will be used to analyse electrolytes and ionic regulators involved with the function of your thigh muscle. All blood samples collected will be used to analyse electrolytes involved during exercise. In the event of any excess blood or tissue remaining it will be disposed of in a de-identified container (i.e. no coding present) via incineration using Victoria University's waste disposal contractor. Performance measures taken during the study will be analysed and stored on the password protected computers of the principal investigators and the student researcher. The data that will be collected during the study will be used/published in peer-reviewed journals and conference presentations. No personal details will be revealed without your written consent. All questionnaire data taken during the study will be used for selection of participants and stored at Victoria University in a locked filling cabinet in the office of the principal; investigator Dr. Rob Aughey. Questionnaire data of participants not selected for the study will be destroyed.

What are the potential risks of participating in this project?

The incremental exercise test involves the unlikely risk of sudden death due to myocardial infarct, vasovagal episodes, muscle soreness and stiffness. Probable risks associated with venous catheterisation include discomfort, bruising and the possible risk of infection (for example puss, tenderness and/or redness). Probable risks associated with muscle biopsy include discomfort, pain, bruising, bleeding, soreness, localised altered sensation of skin reduced/absent/tingle/hypersensitive) and the possible risk of infection. Probable risk associated with blood sample includes slightly uncomfortableness, with possibility of bruising and the possible risk of infection. Risks associated with the $NaHCO_3$ ingestion include gastro-intestinal discomfort. There is the possible psychological risk of

anxiety and apprehension due to the invasive procedures involved with the study. This risk will be minimalised by using qualified and experienced medical staff for all invasive procedures. Additionally access to a registered psychologist is provided to all participants (details below).

How will this project be conducted?

There will be three main phases to the study, Phase 1 (familiarization and variability testing), Phase 2 (double baseline testing and acute exercise) and Phase 3 (training and post-testing) (Figure 1)

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Phase 1: Familiarization and variability testing

During Phase 1 participants will attend the laboratory four times. During the first visit participants will undertake an incremental exercise test on a motorised treadmill to determine aerobic fitness measures

($\dot{V}O_{2peak}$ – peak aerobic capacity). Following the incremental exercise test participants will perform their first familiarisation session for the repeat sprint exercise (RSE) protocol, which consists of three sets of five sprint repetitions lasting 4 seconds each. All RSE will be performed on a non-motorised treadmill. At least 48 hours after the incremental exercise test participants will return for their second visit in which they will perform the Yo-Yo Intermittent Recovery Test Level 1 (IR 1). The third visit will be the first variability testing session in which participants will perform the repeat sprint exercise (RSE) protocol. The fourth visit will occur at least four days after the first variability session and will be identical to the first variability session.

Phase 2: Double baseline and acute exercise

During Phase 2 participants will attend the laboratory for double baseline testing, at least four days after the variability testing. At the first baseline testing session participants will perform the RSE. All participants will ingest either the placebo or experimental substance 60 mins prior to exercise. A venous cannulation (detailed above) will be performed and blood samples will be taken from the antecubital vein (located at the forearm) prior to placebo ingestion, 60, 30 and 10 mins prior to exercise, immediately prior to the 1st sprint, during the 3rd sprint and immediately after the 5th sprint of each set and 5, 10 and 30 mins and 3 hours post RSE. A muscle biopsy will be taken from the vastus lateralis (upper thigh) prior to, immediately post and 3 hours post exercise. After 1 week of recovery, participants will visit the laboratory for their second baseline testing session. This session will also act as the acute exercise trial and the pre-testing session for Phase 3. Participants will be randomly assigned to either Group 1 (Control) or Group 2 (Experimental). Group 1 will ingest the placebo substance ($CaCO_3$) while Group 2 will ingest $NaHCO_3$ 60 mins prior to exercise. Participants will then perform the RSE. Blood and muscle sampling will occur at the same time points as the first baseline testing session.

Phase 3: Training and post-testing

Participants will be asked to train for four weeks, three times a week for a total of 12 sessions. Each session will be supervised by the student investigator (Mr, Matthew Varley). Prior to each training session Group 1 will ingest the placebo while Group 2 will ingest $NaHCO_3$, both 60 mins before RSE. Participants will be required to keep a training diary to monitor any exercise performed outside the trial. During the 6th training session a venous blood cannulation will be performed and samples will be taken from the antecubital vein at the same time points as in Phase 2. The day following the 10th training session participants will be asked to repeat the Yo-Yo IR1. On the day following the 11th training session participants will be asked to repeat the graded exercise test. At least 48 hours after the final training session participants will attend the laboratory for the post-training trial. During this trial venous blood and muscle biopsy measures will be taken at the same time points as during the pre-testing trial.

Who is conducting the study?

This study is being conducted by Victoria University, Faculty of Arts, Education and Human Development, School of Sport and Exercise Science.

If you become stressed as a result of your participation please feel free to consult Dr Harriet Speed a registered psychologist free of charge on (03) 99195412 or at harriet.speed@vu.edu.au

For further information regarding this study please contact the Principal Researcher, Dr Robert Aughey, ph, 9919 5551, mobile 0448 153 597; email robert.aughey@vu.edu.au or Student Researcher, Matthew Varley, ph, 9919 4207, mobile 0419 628 451; email matthew.varley@live.vu.edu.au

Any queries about your participation in this project may be directed to the Principal Researcher listed above.

If you have any queries or complaints about the way you have been treated, you may contact the Ethics and Biosafety Coordinator, Victoria University Human Research Ethics Committee, Victoria University, PO Box 14428, Melbourne, VIC, 8001 phone (03) 9919 4148.

APPENDIX B. INFORMED CONSENT FORM

B.1 Study one - Informed consent

CONSENT FORM FOR PARTICIPANTS INVOLVED IN RESEARCH

INFORMATION TO PARTICIPANTS:
We would like to invite you to be a part of a study investigating the validity and reliability of a 5 Hz Global Positioning System for measuring acceleration in team sports

CERTIFICATION BY SUBJECT

I,

_____

of

_____

certify that I am at least 18 years old* and that I am voluntarily giving my consent to participate in the study:
Validity and reliability of a 5 Hz Global Positioning System for measuring accelerations in team sports
being conducted at Victoria University by: Dr 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:

Matthew Varley

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

- Wear 3 GPS units during a 30m linear acceleration trial
- Perform 120 bouts of a 30m linear acceleration trial at a range of constant velocities and accelerations
- Exposure to a Class 1 laser, which by European Standards is not harmful to the human eye

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

Signed:

Date:

Any queries about your participation in this project may be directed to the researcher
Principal Researcher, Dr Robert Aughey, ph, 9919 5551, mobile 0448 153 597; email robert.aughey@vu.edu.au.

If you have any queries or complaints about the way you have been treated, you may contact the Ethics & Biosafety Coordinator, Victoria University Human Research Ethics Committee, Victoria University, PO Box 14428, Melbourne, VIC, 8001 phone (03) 9919 4148.

B.2 Study two - Informed consent

CONSENT FORM FOR PARTICIPANTS INVOLVED IN RESEARCH

INFORMATION TO PARTICIPANTS:
We would like to invite you to be a part of a study investigating the acceleration and high-intensity activity demands of elite soccer players.

CERTIFICATION BY SUBJECT

I,

_____

of

_____

certify that I am at least 18 years old* and that I am voluntarily giving my consent to participate in the study:
Acceleration and fatigue in elite soccer: An in-depth analysis of high-intensity activity being conducted at Victoria University by: Dr 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:

Matthew Varley

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

- Provide the researcher (Matthew Varley) permission to access and analyse the GPS data files collected during matches

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

Signed:

Date:

Any queries about your participation in this project may be directed to the researcher
Principal Researcher, Dr Robert Aughey, ph, 9919 5551, mobile 0448 153 597; email robert.aughey@vu.edu.au.
If you have any queries or complaints about the way you have been treated, you may contact the Ethics & Biosafety Coordinator, Victoria University Human Research Ethics Committee, Victoria University, PO Box 14428, Melbourne, VIC, 8001 phone (03) 9919 4148.

B.3 Study three - Informed consent

CONSENT FORM FOR PARTICIPANTS INVOLVED IN RESEARCH

INFORMATION TO PARTICIPANTS:

We would like to invite you to be a part of a study investigating **the effects of sodium bicarbonate ingestion on ionic regulation and performance during repeated-sprint exercise training**

- Participant involvement and overview of testing - Participants will be requested to attend the Exercise Physiology Laboratory at Victoria University, Footscray Park Campus (Room L305, building L) on six separate occasions for exercise testing trials, 4 weeks of training and another three testing trials.

- Exercise Testing – Participants will be asked to undertake an incremental exercise test and a Yo-Yo Intermittent Recovery Test on several occasions.

- Training Program – Participants will be asked to train for 4 weeks, three times a week, in order to obtain marked adaptations in their aerobic system. Each training session consists of 3 sets of five 4-sec sprints conducted on a non-motorized treadmill, with 20 seconds of recovery between the repetitions and 4.5 minutes rest between sets.

- Supplementation – Sodium bicarbonate and calcium carbonate supplementation will occur 60 minutes prior to exercise on 16 occasions; 2 baseline trials, 12 training sessions and 1 post-training trial. Supplements will be taken with 500 ml of water via 12 – 16 gelatine capsules.

- Muscle Biopsies – The muscle biopsy procedure is used to obtain small samples of your muscle tissue for analysis of metabolites and ionic regulators. During both baseline trials and the post-training trial, muscle biopsies will be taken from the thigh muscle of participants, at rest, post exercise and 3 hours post exercise. Three biopsies will be taken on each visit, for a total of nine biopsies. During the procedure you will feel pressure and this will be quite uncomfortable and you may also experience some pain, but this will last for only about 1-2 seconds. Muscle biopsies are routinely carried out in our laboratory, with no serious adverse effects.

- Venous Cannulation – Blood samples will be taken during rest, exercise and recovery via a catheter placed in the arm. This procedure allows the taking of multiple blood samples without the need for multiple venepuncture (puncturing of the vein). Cannulation is slightly uncomfortable, with minimal possibility of bruising and infection.

CERTIFICATION BY SUBJECT

I,

_____

of

_____

certify that I am at least 18 years old* and that I am voluntarily giving my consent to participate in the study: **The effects of sodium bicarbonate ingestion on ionic regulation and performance during repeated-sprint exercise training**
being conducted at Victoria University by: Dr 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:

Matthew Varley

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

- Screening
- $\dot{V}O_{2peak}$ testing
- Yo-Yo IR1 test
- Repeat Sprint Test and training
- Muscle Biopsies
- Venous catheterisation and blood sampling
- Sodium bicarbonate and calcium carbonate ingestion

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

Signed:

Date:

Any queries about your participation in this project may be directed to the researcher
Principal Researcher, Dr Robert Aughey, ph, 9919 5551, mobile 0448 153 597; email robert.aughey@vu.edu.au.
If you have any queries or complaints about the way you have been treated, you may contact the Ethics & Biosafety Coordinator, Victoria University Human Research Ethics Committee, Victoria University, PO Box 14428, Melbourne, VIC, 8001 phone (03) 9919 4148.

APPENDIX C. RAW DATA

C.1 Plasma volume data from Chapter 5

Table C-1 Change in plasma volume (%) from -90 during RSE and recovery during PRE testing for EXP group

	-90	-10	Pre-Set1	Set2	Pre-Set2	Set2	PreSet3	End	+1	+2	+5	+10	+20	+30
Participant 1	0	4.61	-2.18	-7.89	-7.65	-10.59	-8.5	-7.88	-12.87	-7.08	-6.52	-2.96	6.23	19.34
Participant 2	0	6.89	-6.47	-11.45	-9.28	-14.27	-12.37	-12.96	-12.25	-7.11	-9.96	-4.5	3.37	8.4
Participant 3	0	5.34	-13	-15.02	-12.08	-13.47	-11.84	-11.31	-11.57	-10.26	-10.35	-5.57	1.28	7.59
Participant 4	0	-2.01	-11.68	-12.89	-12.05	-16.16	-12.86	-14.51	-14.43	-7.51	-7.35	-0.61	1.75	1.34
Participant 5	0	-4.72	-13.97	-16.19	-13.9	-17.58	-14.83	-15.97	-15.42	-12.87	-9.34	-1.24	8.1	10.35
Participant 6	0	-7.84	-17.2	-17.25	-20.58	-20.27	-20.97	-26.39	-22.96	-21.26	-17.9	-12.45	-8.22	-2.7
Participant 7	0	-7.61	-13.05	-18.35	-19.35	-20.85	-19.05	-18.89	-17.24	-16.4	-8.47	-10.62	-7.2	-2.53
Mean	0	-0.76	-11.08	-14.15	-13.56	-16.17	-14.35	-15.41	-15.25	-11.79	-9.98	-5.42	0.76	5.97
SD	0	6.31	5.07	3.66	4.84	3.71	4.34	5.96	3.92	5.43	3.75	4.54	6.27	7.91

Table C-2 Change in plasma volume (%) from -90 during RSE and recovery during ACUTE testing for EXP group

	-90	-10	Pre-Set1	Set2	Pre-Set2	Set2	PreSet3	End	+1	+2	+5	+10	+20	+30
Participant 1	0	5.77	-3.41	-7.86	-8.71	-16.12	-11.65	-12.85	-10.99	-8.18	-11.72	-2.38	2	9.75
Participant 2	0	6.1	-6.45	-11.34	-9.83	-11.3	-8.42	-7.51	-5.67	-4.31	-1.58	2.88	9.2	12.22
Participant 3	0	10.95	-4.96	-7.54	-8.7	-7.06	-8.4	-5.65	-4.76	-1.27	8.19	8.12	14.7	20.95
Participant 4	0	2.18	-6.88	-11.16	-10.08	-12.31	-8.4	-9.18	-6.98	-6.12	-2.91	-1.06	5.98	10.87
Participant 5	0	-1.62	-8.19	-11.54	-7.56	-11.54	-8.5	-10.21	-10.38	-11.14	-5.54	-1.76	1.32	10.87
Participant 6	0	0.41	-15.68	-15.96	-17.76	-17.83	-14.36	-18.18	-20	-18.5	-14.36	-7.53	-1.59	1.15
Participant 7	0	2.43	-7.24	-12.36	-13.04	-14.57	-13.31	-16.63	-14.51	-12.89	-12.81	-10.17	-3.45	3.69
Mean	0	3.74	-7.54	-11.11	-10.81	-12.96	-10.43	-11.46	-10.47	-8.92	-5.82	-1.7	4.02	9.93
SD	0	4.2	3.92	2.85	3.52	3.57	2.62	4.65	5.41	5.78	7.95	6.11	6.37	6.38

Table C-3 Change in plasma volume (%) from -90 during RSE and recovery during POST testing for EXP group

	-90	-10	Pre-Set1	Set2	Pre-Set2	Set2	PreSet3	End	+1	+2	+5	+10	+20	+30
Participant 1	0	1.8	-9.84	-18.93	-15.18	-18.6	-17.7	-19.37	-15.22	-15.77	-12.68	-4.17	-7.13	-3.88
Participant 2	0	3.27	-7.48	-13.93	-12.97	-15.23	-13.81	-12.52	-11.69	-13.06	-7.15	-6.35	5.49	9.29
Participant 3	0	2.73	-15.2	-14.33	-16.61	-22.59	-18.64	-8.55	-15.7	-16.85	-10.17	3.05	5.81	1.59
Participant 4	0	-6.23	-13.39	-15.74	-16.17	-16.77	-16.13	-15.27	-17.45	-8.85	-10.82	-9.23	-0.24	1.74
Participant 5	0	-2.02	-14.29	-17.41	-15.87	-18.56	-17.28	-16.8	-6.39	-15.01	-5.08	-6.78	0.22	5.48
Participant 6	0	-6.09	-16.84	-21.14	-20.93	-20.28	-21.7	-21.47	-21.38	-19.73	-14.73	-9.1	-2.68	1.54
Participant 7	0	-3.63	-13.54	-21.43	-19.21	-20.17	-19.99	-24.25	-21.59	-9.07	-16.37	-10.04	-10.5	-6.69
Mean	0	-1.45	-12.94	-17.56	-16.71	-18.89	-17.89	-16.89	-15.63	-14.05	-11	-6.09	-1.29	1.29
SD	0	4.08	3.22	3.07	2.63	2.42	2.57	5.36	5.37	4.01	4	4.52	6.06	5.36

Table C-4 Change in plasma volume (%) from -90 during RSE and recovery during PRE testing for CON group

	-90	-10	Pre-Set1	Set2	Pre-Set2	Set2	PreSet3	End	+1	+2	+5	+10	+20	+30
Participant 1	0	3.32	-8.14	-11.6	-9.63	-9.38	-5.26	-10.8	-8.7	-7.27	-4.6	0.66	6.15	9.34
Participant 2	0	0.85	-7.38	-7.83	-9.02	-10.12	-7.6	-5.15	-1.54	-4.37	-2.08	-3.06	7.5	7.22
Participant 3	0	-3.85	-12.75	-15.07	-14.48	-16.83	-16.38	-13.19	-12.64	-15.15	-11.13	-11.53	-5.74	-5.17
Participant 4	0	-2.91	-12.3	-16.92	-15.12	-18.7	-15.72	-16	-14.13	-12.4	-9.34	-2.61	0.72	2.08
Participant 5	0	-1.55	-14.99	-18.52	-17.36	-18.98	-19.85	-21.98	-21.11	-17.79	-16.76	-12.64	-6.97	-3.14
Participant 6	0	-0.93	-11.38	-16.2	-15.32	-17.54	-15.37	-16.57	-17.14	-15.68	-14.71	-10.03	-8.97	4.19
Participant 7	0	-5.25	-15.64	-20.06	-18.91	-23.67	-19.91	-22.56	-19.24	-20.06	-12.8	-9.2	-4.49	-1.4
Mean	0	-1.47	-11.8	-15.17	-14.26	-16.46	-14.3	-15.18	-13.5	-13.24	-10.2	-6.91	-1.68	1.87
SD	0	2.9	3.14	4.2	3.7	5.08	5.72	6.15	6.72	5.65	5.31	5.16	6.54	5.41

Table C-5 Change in plasma volume (%) from -90 during RSE and recovery during POST testing for CON group

	-90	-10	Pre-Set1	Set2	Pre-Set2	Set2	PreSet3	End	+1	+2	+5	+10	+20	+30
Participant 1	0	-2.87	-12.81	-16.79	-11.44	-15.24	-13.27	-8.39	-11.52	-11.13	-7.31	-4.31	5.77	6.46
Participant 2	0	4.21	-0.5	-8.51	-7.29	-9.47	-9.01	-9.55	-2.54	-5.32	-1.11	4.39	8.98	12.8
Participant 3	0	3.5	-6.56	-14.48	-11.29	-14.18	-12.97	-13.18	-12.62	-10.4	-9.18	-6.54	-2.15	0.79
Participant 4	0	-0.12	-15.6	-19.58	-18.22	-21.2	-18.8	-20	-20.57	-16.22	-14.93	-2.74	-4.47	1.94
Participant 5	0	-2.54	-16.08	-16.3	-19.37	-18.16	-20.62	-20.07	-16.87	-20.31	-17.91	-6.93	-4.08	-0.07
Participant 6	0	4.2	-3.82	-8.93	-5.11	-13.72	-11.66	-12.82	-11.58	-10.36	-4.6	-4.35	-1.37	4.56
Participant 7	0	1.24	-14.2	-19.24	-16.44	-20.42	-20.37	-18.66	-14.11	-11.41	-12.1	0.86	-2.95	1.57
Mean	0	1.09	-9.94	-14.83	-12.74	-16.06	-15.24	-14.67	-12.83	-12.17	-9.59	-2.8	-0.04	4.01
SD	0	3.04	6.25	4.52	5.47	4.14	4.63	4.91	5.58	4.79	5.86	4.1	5.25	4.49