Victoria University

Institute for Health and Sport

Exploring the Transfer from Drills to Skills in Elite Freestyle Swimming

Victoria Brackley

BEngSc (Sports Engineering)

BAppSc (Human Movement) (Honours)

Submitted in fulfilment of the requirement for the degree of

DOCTOR OF PHILOSOPHY

December 2020

Abstract

Practice tasks that decompose the skill into smaller components are routinely prescribed by coaches to improve biomechanical qualities for efficient and fast swimming. Such practice tasks are typically referred to as drills and prescribed within part-whole training approaches. The Representative Learning Design (RLD) framework suggests that task decomposition may lack the capability to represent or transfer to the behavioural and movement skills required in competition. Consequently, current practice in swimming may be sub-optimal. This thesis aimed to examine the efficacy of current swimming practice approaches for improving competition performance. To address this concern, this thesis was broken into three studies. **Study One (Chapter 3)** explored the most commonly prescribed training approaches used by elite swimming coaches to improve freestyle stroke technique. The findings indicated that swimming coaches seem to intuitively mention using variants of the constraints-led approach in their practice design. However, in practice, tasks that decompose the skill into smaller components are prioritised. This study provided the foundation to representatively assess the immediate effect task decomposition drills have in supporting freestyle performance. **Chapter 4** encapsulated the design and calibration of a swimming 3D kinematic analysis system to allow for drill and freestyle analysis. The eight camera, multi-digital setup allowed for a reliable and accurate quantification of the multi-planar swimming movement. In **Study Two and Three (Chapter 5 and 6)**, the action fidelity of two commonly prescribed upper-limb drills, *Long Dog* and *Polo*, were kinematically assessed using group- and individual-based analysis approaches. Six elite freestyle specialists swam a total of 300 m, for each drill, broken into two 25 m laps of drill then two 25 m laps of freestyle swimming. A number of significant kinematic differences and similarities were identified between drill and freestyle swimming. On a group basis, paired t-tests indicated that when swimming the *Long Dog* drill participants displayed no significant differences in upper-limb characteristics compared to freestyle, yet may not represent the medial-lateral hand pull path of race-pace freestyle. The *Polo* drill returned similar upper-limb kinematic characteristics to that encouraged for sprint-distance swimmers. Further, the results suggested that the *Polo* drill could lead to higher stroke rate values and inter-arm coordination that may be beneficial to race-pace freestyle. Individual-based analysis revealed that participants displayed significant individual-specific differences between freestyle and drill swimming. This indicated that certain drills may not be as beneficial for particular swimmers', based on their distance specialisation and skill level. A combination of both group- and individual-based analysis provided a thorough examination of the effect of drill swimming on freestyle kinematics and performance. The body of work in this thesis provides both detailed insights into elite swimming coaches prescription of training tasks and empirical evidence to confirm or question current task decomposition drills.

Student Declaration of Original Authorship

I, Victoria Brackley, declare that the PhD thesis entitled ***Exploring the transfer from drills to skills in elite freestyle swimming*** is no more than 80,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

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

Signature: [redacted] Date: 23 / 12 / 2020

Acknowledgements

Reflecting back over this PhD journey, I'm reminded of what a rollercoaster ride it has been. This experience has taken me on one long adventure which, although tiresome, has been extremely memorable. I've been guided and supported by some incredible people of whom I would like to take the time to acknowledge and thank in the following paragraphs.

To begin, I would like to express a sincere and big thanks to my supervisors – Damian Farrow, Kevin Ball, Elaine Tor and Sian Barris. While a team of four supervisors may seem large, I thought you all brought something unique and valuable to this research project. You guided and supported me in your own individual way which I have taken many valuable lessons from. To Damo, thank you for your consistent guidance, unending knowledge and approachability. I so appreciate your laid-back persona and time you always gave me. To Kev, thank you for being so encouraging and patient with me throughout this journey. I am grateful for the time you always gave me to ask questions and pick your brain. You have challenged my 'thinking' and made me realise that there is very rarely a 'black and white' answer in research. Elaine, you have been a consistent presence throughout my research journey. Thank you for initially introducing me to the world of high-performance sport, swimming and research. You have provided various learning and networking opportunities along this journey which I am grateful for. Sian, thanks for your support throughout crucial stages of my PhD. I hope to continue to learn from you as you definitely have such a creative approach to supporting your athletes and coaches. You also encouraged me at the beginning of my PhD journey that coming from a non-swimming background could be positive approach to this research. Thanks, I so needed and valued the positive affirmation.

To Marc Elipot, I would have been so lost in the 3D swimming space were it not for your support. Thank you for dedicating so much time to help me during the pilot phases of the 3D kinematic testing. I also appreciate all your help throughout the data processing phases. Thanks for reminding me that this PhD journey was not just about the research but also about the skillsets I would learn along the way. I hope manual digitisation is a skill I do not have to use for a while!

Kelly Stubbins, thanks for allowing me to 'shadow' you on pool deck during my first year of my PhD. You allowed me to ask countless questions and helped me understand the swimming jargon (though I still find it difficult to understand the coaches' whiteboard at times). Additionally, the 3D swimming component of my PhD would not have been possible without the assistance from Emily Nicol, Kelsey Wells, Joshua McDermott, Namira Adani and Lana Roden. Thank you all for either helping me set up the pool, run testing sessions or process data. Special mention must go to Emily Nicol, you have officially become my swimming encyclopaedia and I still have the "swimming knowledge and terminology" notebook you made me all those years ago. I appreciate your energy and look forward to our next coffee catch-up. To Change Parts and Select Windows, thanks for allowing me to use your workshops, off-cuts and resources to make the camera frame mounts and calibration frame. To Richard Little, thanks for helping me through the statistical challenges. The analyses would have taken a lot longer without your help.

To all the participants involved in my studies, thank you! To the twenty elite swimming coaches I interviewed, I so enjoyed sitting with all you (drinking coffee, of course) as you downloaded just a portion of your experiential expertise onto me. Thank you for your openness and interest in my work. Special mention must go to Jan Cameron. You are a legend and missed. To the swimmers, thank you for allowing me to put all those markers on you and for participating in my research.

Thanks to Victoria University, Swimming Australia and the Victorian Institute of Sport (VIS) for their support either financially, academically or technically. The joint partnership helped me to continually consider the practically applications of my research. Additionally, I was able to work alongside and with various experts in their respective fields which I benefitted from greatly.

I must also thank my fellow PhD friends I met along the way. A special mention goes to Peter Browne, Aden Kittel and Peter LeNoury. I so enjoyed our friendly banter, long lunches, laughs and chats. I look forward to continuing our friendship in years to come. Also, thanks to the iHeS Analytical and Technology Group. I learnt so much from our catch-ups, guest presentations and journal club.

Thanks to my family and close friends for the unfailing friendship and support. To Hannah and Sarah, thanks for the lasting friendship from kindergarten until now. The long chats and laughs were so necessary. To my older sisters and brothers-in-law Elizabeth, Catherine, Andrew and Ben, thanks for championing your little sis through this journey. While nothing beats being together in person, I'm grateful for FaceTime and our long phone chats. To mum and dad, Stefanie and Martin, thanks for raising me on solid life principles I continue to live by today. I so appreciate our chats, your advice and support. Thanks for helping brainstorm a solution for my swimming calibration frame and jumping in the pool to help pilot the 3D swimming setup. I feel so proud and blessed to have parents like you. Also, thanks mum for reminding me that "I can only do, what I can do".

Finally, thanks to my teenage sweetheart, best friend and husband, Winston (Winnie). Its special to have gone through both our undergraduate and postgraduate degrees together. You truly understood my challenges and were continually supportive. Thanks for always providing a listening hear and asking those annoying questions that really were useful. I also want to acknowledge and congratulate your achievement of working full-time as an engineer and completing your Masters of Geotechnical Engineering! You really are smarter than you think. I thought I would end by quoting the line from Li Na's 2014 Australian Open winner's speech when addressing her husband:

"Thanks a lot. You're a nice guy."

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List of Abbreviations

cycles/min	Stroke cycles per minute
DLT	Direct Linear Transformation
FINA	Fédération Internationale de Natation
Hz	Hertz
m	Metres
m/s	Metres per second
m^2/s	Metres squared per second
$P^{B\text{-}H}$	Bonferroni-Holm correction p-value
RLD	Representative Learning Design
RMS	Root Mean Square
SC	Stroke cycle
SD	Standard deviation
SI	Stroke index
SL	Stroke length
SR	Stroke rate
SV	Swimming velocity
2D	Two-dimensional
3D	Three-dimensional
°	Degrees
%	Percentage
% of SC	Percentage of the stroke cycle

Research Outputs

Chapters within this thesis have been published (or submitted for publication) and/or presented at relevant conferences.

Peer-reviewed journal articles

The following thesis-related work was published during candidature.

Chapter 3: Brackley, V., Barris, S., Tor, E. & Farrow, D. (2020). Coaches' perspective towards skill acquisition in swimming: What practice approaches are typically applied in training?, *Journal of Sports Sciences*. DOI: 10.1080/02640414.2020.1792703

Chapter 5: Brackley, V., Tor, E., Barris, S., Farrow, D. & Ball, K. (2020). The comparison of drill swimming on freestyle kinematics: Group-based analysis. *Currently under second round review*

Chapter 6: Brackley, V., Tor, E., Barris, S., Farrow, D. & Ball, K. (2020). Drill or swim, what should coaches prescribe? Individual-based analysis on the comparison of drill swimming on freestyle kinematics. *Currently under review*

Academic conference presentations

Supporting Chapter 3, the following thesis-related work was peer-reviewed and presented during candidature.

Brackley, V., Barris, S., Tor, E., Farrow, D. (2018). "Training practices in elite swimming: The coaches' perspective." Presented at the 2018 Australasian Skill Acquisition Network (ASAN) conference, Sydney, Australia.

Supporting Chapters 5 and 6, the following thesis-related work was peer-reviewed and presented during candidature.

Brackley, V., Tor, E., Barris, S., Farrow, D., Ball, K. (2020). "The prescription and effect of drill swimming of freestyle kinematics." Present at the 2020 Exercise and Sport Science Australia (ESSA) Sport Science Twitter Conference (online).

Brackley, V., Tor, E., Barris, S., Farrow, D., Elipot, M., Ball, K. (2020). "The effect of *Polo* drill swimming on freestyle kinematics: A pilot study." Presented at the 38th Conference for International Society of Biomechanics in Sport (ISBS) (online). Manuscript published in the ISBS Proceedings Archive: Vol. 38: Iss. 1, Article 134.

Supporting Chapters 5 and 6, the following thesis-related work was presented during candidature.

Brackley, V. (2020), “The prescription and effect of drill swimming of freestyle kinematics.” Presented at the 2020 Victoria University HDR Conference, Melbourne, Australia.

Brackley, V. (2019). “Swimming training practices: Do the drills help develop the skills?” Presented at the 2019 Victoria University HDR Conference, Melbourne, Australia.

Brackley, V. (2018), “Exploring the transfer from drills to skills in elite freestyle swimming.” Poster presented at the 2018 Victoria University HDR Conference, Melbourne, Australia.

Invited applied presentations

The following thesis-related work was presented during candidature.

Brackley, V. (2020). "The prescription and effect of drills on freestyle swimming performance." Presented at the September, 2020 Institute for Sport and Health e-Seminar Series, Melbourne, Australia.

Brackley, V. (2018). "Exploring the transfer from drills to skills in freestyle swimming: PhD update – studies 1 & 2." Presented at the October, 2018 Australian Analysis and Research Group for Optimisation in Swimming (AARGOS) meeting, Melbourne, Australia.

Brackley, V., Veliades, N. & Tor, E. (2017). "Integrating skill development in the daily training environment." Presented at the 2017 Australian Swimming Coaches and Teachers Association – Victoria (ASCTAV), Melbourne, Australia.

Other

Brackley, V., "Swimming training practices: Do the drills help develop the skills?" Finalist at the 2019 Victoria University Three Minute Thesis Competition, Melbourne, Australia.

Brackley, V. (2018). Considerations when designing practice tasks in swimming. Summary article for Skill Acq Science, https://skillacqscience.com/2018/01/29/considerations-when-designing-practice-tasks-in-swimming/

Chapter 1: Introduction and Thesis Outline

1.1 Introduction

Consider for a moment that the difference between standing on the winner's podium and not, is often a matter of milliseconds in elite swimming. Consequently, it is no surprise that coaches, sport scientists and researchers are on a continual quest to improve key skills and swimming technique that can help their swimmer touch the wall first. In competition, freestyle is the fastest stroke (Seifert, Boulesteix, Carter, & Chollet, 2005; Skorski, Faude, Caviezel, & Meyer, 2014). It is characterised by alternating overhead arm actions, rotating 360° around the shoulder, and varying number of near-vertical, pendulum leg kicks (Guignard et al., 2019; Wannier, Bastiaanse, Colombo, & Dietz, 2001; Yanai & Wilson, 2008). The upper-limb actions provide around 68% of total propulsion in freestyle swimming, whereas the lower-limb actions contribute to around 31% (Morouço, Marinho, Izquierdo, Neiva, & Marques, 2015; Swaine, Hunter, Carlton, Wiles, & Coleman, 2010). The greater contribution of the upper-limbs to total propulsion has led to extensive biomechanical research on upper-limb kinematics and kinetics where the motion of the hand is commonly considered the main instrument of propulsion (Chollet, Chalies, & Chatard, 2000; Seifert, Chollet, & Rouard, 2007; Sobrino, Fernández, & Navandar, 2017). To help develop or improve specific stroke characteristics, many swimming coaching textbooks advocate the use of drill-based practice tasks (Guzman, 2007; Lucero, 2015; Maglischo, 2003).

A common drill-based practice task includes breaking the skill into smaller components (Ford, Yates, & Williams, 2010; Renshaw, Chow, Davids, & Hammond, 2010; Travassos, Duarte, Vilar, Davids, & Araújo, 2012). This is typically referred to as task decomposition or part-task practice. The rationale for task decomposition or part-task practice is to improve the consistency of each smaller skill component in isolation so that when incorporated back into the full skill, consistency gained in each part is visible in the skill itself (Davids, Glazier, Araújo, & Bartlett, 2003). In swimming, for example, coaches may prescribe the single-arm drill which is full freestyle swimming reduced to single arm freestyle, with the resting arm close to the body. The purpose of this drill is to allow the athletes to focus on breath timing and body alignment (Arellano, Domínguez-Castells, Perez-Infantes, & Sánchez, 2010; Lucero, 2015). While well intentioned, there is no empirical evidence to suggest that breath timing and body alignment is reinforced during the single-arm drill. Nor is there any evidence that this drill positively influences these parameters in the form of learning and performance in competition. Rather, it is argued that whole training approaches may better facilitate skill learning for continuous and repetitive tasks, such as swimming (F. E. Fontana, Furtado Jr, Mazzardo, & Gallagher, 2009).

Skill acquisition advocates the need to design practice tasks that represent the constraints and specific performance demands required for competition (Araújo, Davids, & Passos, 2007; Krause, Farrow, Reid, Buszard, & Pinder, 2018; Pinder, Davids, Renshaw, & Araújo, 2011b). The Representative Learning Design (RLD) framework assists coaches, sport scientists and researchers in designing practice and experimental tasks that are representative of the specific context they are attempting to simulate (Pinder, Davids, et al., 2011b). It has been suggested that training tasks that replicate key information from the performance setting are likely to produce learning outcomes that can be applied in competition, therein enhancing performance (Vilar, Araújo, Davids, & Renshaw, 2012). While the concept is intuitively appealing and has renewed interest in exploring performance more holistically, there appears to be a disconnect between the contentions of contemporary skill acquisition literature and the practice prescribed in the applied setting (Dehghansai, Headrick, Renshaw, Pinder, & Barris, 2019; A. M. Williams, Ford, Causer, Logan, & Murray, 2012; A. M. Williams & Ford, 2009).

Training observations and coaching textbooks suggest that swimming coaches prescribe drills that decompose the stroke into component parts (Junggren, Elbæk, & Stambulova, 2018; Neiva, Marques, Barbosa, Izquierdo, & Marinho, 2014; Neiva, Marques, Fernandes, et al., 2014). However, empirical findings from sports like diving, tennis and cricket have identified that practice tasks that decompose the skill may not represent the movement or behavioural responses required in competition performance (Barris, Davids, & Farrow, 2013; Pinder, Renshaw, Davids, & Kerhervé, 2011; Reid, Giblin, & Whiteside, 2015). As the RLD frameworks argues that functional learning is dependent on the extent to which practice tasks are representative of the competition context, there is clear scope for research to further examine current swimming practice tasks.

Despite the growing number of studies providing examples of how RLD can be applied in sporting contexts to benefit practice design (Krause, Farrow, Buszard, Pinder, & Reid, 2019), no empirical work has assessed swimming practice tasks using theoretical underpinnings from RLD. To date, only two studies have examined the immediate effect drills have on biomechanical parameters of freestyle swimming (n = 8, Spanish national age-group swimmers and n = 13, Spanish regional swimmers) (Arellano et al., 2010; López, Gutiérrez, & Arellano, 2002). Whilst both studies provided an initial understanding of the immediate effect the single-arm drill has on the freestyle stroke, only a limited number of parameters were assessed as the investigations were restricted to either sagittal plane analysis or a small underwater calibration area (4.0 x 2.0 x 2.0 m). Further, the key parameters expected to be improved by the single-arm drill (i.e., breath timing and body alignment) were not specifically assessed or considered. Expanding upon these studies and investigating the key biomechanical characteristics that various drills target is needed to provide a more comprehensive understanding of drills in freestyle swimming. This information is important for coaches in the design and prescription of representative tasks in training.

An important methodological consideration needed in the examination of freestyle performance or freestyle drill performance is the purpose of analysis and swimming parameters under investigation (Mooney, Corley, Godfrey, Os-borough, et al., 2015). This ensures that the most reliable and accurate measurement system is used to quantify the multi-planar swimming movement (Psycharakis, Sanders, & Mill, 2005; Sanders et al., 2012). For the kinematic assessment of freestyle performance, a multi-digital camera setup for three-dimensional (3D) quantitative analysis is recommended (Psycharakis et al., 2005; Sanders, Chiu, et al., 2015; Sanders et al., 2012). A prerequisite for the accurate quantification of the multi-planar swimming movement is an accurate calibration of the 3D space to ensure the 3D coordinate reconstruction is accurate (Abdel-Aziz & Karara, 1971; Psycharakis et al., 2005). Consequently, this thesis utilised specific and unique processes to allow for accurate 3D kinematic analyses in swimming.

In order to kinematically assess specific skill movements, in elite sport, a combination of both group- and individual-based analysis has been recommended (Ball & Best, 2012; Ball, Best, & Wrigley, 2003a, 2003b). Group-based analysis can provide initial insights into the effect of drill swimming on key performance parameters. However, individual-based analysis is also needed in order to account for individual variations in swimming technique which can often be masked in a group-based analysis (Ball & Best, 2012; Ball et al., 2003a, 2003b). Traditionally, swimming investigations have used group-based analysis approaches to examine and identify statistical kinematic differences between groups (Deschodt, Arsac, & Rouard, 1999; McCabe, Psycharakis, & Sanders, 2011; Seifert, Chollet, & Bardy, 2004). As individual-specific differences exist in regards to swimmers' own anthropometric and mechanical characteristics (Seifert, Button, & Brazier, 2010; Seifert, Button, & Davids, 2013), the assessment of freestyle and drill swimming technique should also include an individual-based analysis approach. If individual differences exist in drill swimming technique, coaches may need to tailor the prescription of drills to the individual rather than using the same drill for all participants, especially at the elite level.

This thesis sought to qualitatively and quantitively investigate swimming practice designs through the lens of the RLD framework. Freestyle swimming was selected as the stroke to investigate in this thesis due to the amount of existing research on the biomechanical features critical to freestyle performance (Guignard et al., 2019; Sanders, Andersen, & Takagi, 2017; Toussaint & Beek, 1992), yet a corresponding lack of empirical evidence supporting current practice tasks prescribed by coaches to help develop these features.

1.2 Aims of thesis

1.2.1 General aim

This thesis aimed to examine the efficacy of current swimming practice approaches for improving key movement and skill characteristics expected in freestyle competition performance. Two specific aims were formulated.

1.2.2 Specific aims

1. Identify the current practice approaches prescribed by elite swimming coaches for developing freestyle technique and align these against the RLD framework (Chapter 3).
2. Biomechanically compare movement kinematics between freestyle and commonly prescribed freestyle drills from a group- and individual-based analysis approach (Chapter 5 and 6).

1.3 Thesis structure and chapter organisation

This thesis is presented in a traditional format and includes a combination of initial background literature and chapters that are based on published manuscripts or work submitted for peer-review. Consequently, there is a portion of content repetition in three of the chapters (Chapters 3,5 and 6) so that they can be read as standalone articles. This also allows each study within these chapters to demonstrate its contribution and impact to the existing literature separately. Specifically, this thesis is presented in five sections (see Figure 1.1).

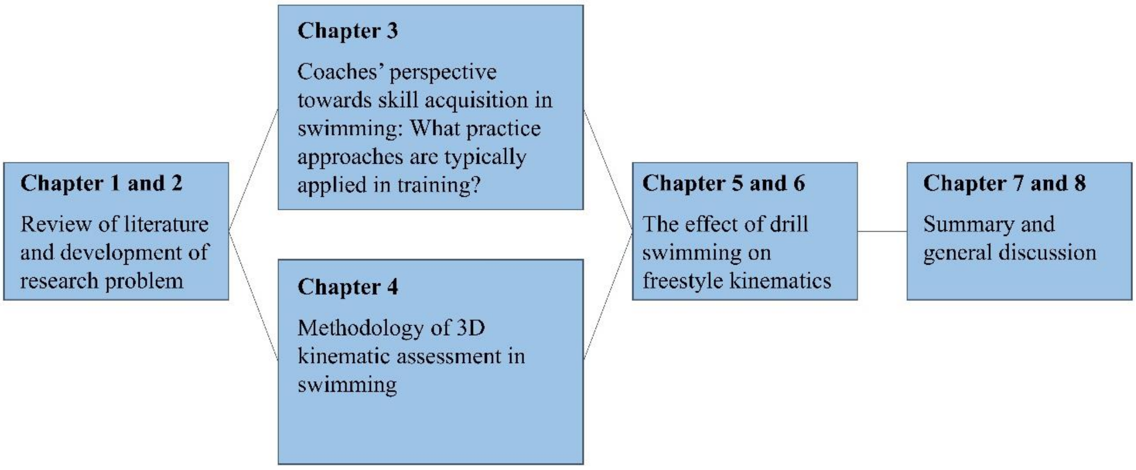


Figure 1.1 Thesis structure and overview.

The first section of the thesis provides an introduction to the research question, providing a brief rationale for the research and detailed the specific aims to be addressed within this thesis (Chapter 1). Chapter 2 considers and critiques literature encompassing the study of skill learning and practice design. The focus is on the underpinning theoretical approaches used to designing more representative practice and experimental tasks. In order to biomechanically assess current practice design in swimming, relevant kinematic measurement parameters and techniques are also evaluated.

The second section (Chapter 3), referred to as Study One, provides qualitative analysis of the current practice approaches employed by elite swimming coaches to develop and improve freestyle swimming technique. Coaches' theoretical approach to skill learning, specific freestyle drill types and training strategies were explored.

With an understanding of the practice approaches typically uses by coaches to improve freestyle swimming technique, Chapter 4 details the methodology employed to biomechanically assess the most commonly prescribed freestyle drills[1]. To enable the 3D

[1] This thesis initially proposed to examine four of the most commonly prescribed freestyle drills; hence the 3D methodology design considered all drills. However, due to the expanded scoped of the 3D kinematic design and setup, the focus of the thesis changed to include the two most commonly prescribed upper-limb freestyle drills only.

kinematic assessment of the freestyle drills within the applied setting, specific above- and below-water camera mounts were designed. This also included the manufacture of a calibration frame. Further, the DLT method was utilised as the data processing technique to identify selected variables.

The fourth section encompasses Study Two and Three (Chapters 5 and 6). These studies investigated the effect of drill swimming on freestyle kinematics from a group- and individual-based analysis approach, respectively. The two drills examined include *Polo* and *Long Dog*. These drills were identified from Study One (Chapter 3) as two of the most commonly prescribed upper-limb freestyle drills. Both drills decompose the stroke; that being, in *Long Dog* the above-water recovery action is removed and in *Polo* the breathing action is removed by having the swimmer's head above water.

In the final section (Chapter 7), a summary and general discussion of the experimentation chapters were discussed. Theoretical and practical implications were considered, along with limitations and future research directions.

Chapter 2: Review of Literature

2.1 Introduction

The development of an athlete, from basic performance to an elite level of accomplishment, requires thousands of hours of practice and the fine tuning of skills (Baker & Farrow, 2015; Ericsson, Krampe, & Tesch-Römer, 1993). Even though the number of hours dedicated to practice is important for developing expert skills, the practice approach has been identified as being equally, if not greater in importance (Davids, 2000). Drill-based practices such as task decomposition and part-task practices are examples of popular and traditional practice approaches adopted by coaches in a variety of sports to help facilitate technique correction and learning. While such practice approaches may facilitate some skill learning, there is a debate within skill acquisition literature as to whether the skills acquired during such practice approaches effectively simulate key informational and movement demands required in the intended performance environment (Barris, Farrow, & Davids, 2013; Pinder, Davids, et al., 2011b; Seifert et al., 2013). Specifically, decomposing the full freestyle stroke into a single arm drill can cause movement solutions that are less generalisable and transferable to the competition context (Arellano et al., 2010).

This review introduces concepts from ecological dynamics and describes the importance of the continuous coupling that athletes share with their environment (Araújo, Davids, & Hristovski, 2006; Davids, Araújo, Hristovski, Passos, & Chow, 2012). Secondly, Representative Learning Design (RLD) is introduced as a theoretical framework to assess current practice approaches prescribed, namely drill-based practices, in the sport of swimming. Third, as the type of practice athletes engage in can greatly affect functional learning (Farrow, Baker, & MacMahon, 2013), this review of the literature considers and critiques current practice approaches used by coaches to teach and improve skill learning for competition performance. Lastly, specific kinematic measurement parameters and techniques used in swimming biomechanical research are evaluated. This review of literature demonstrates the importance of considering the extent to which freestyle swimming practice represents the informational and movement behaviours encountered in the racing performance context (Krause, Farrow, Buszard, et al., 2019; Pinder, Davids, Renshaw, & Araújo, 2011a; Pinder, Davids, et al., 2011b).

2.2 Theoretical underpinnings of representative learning design

The RLD framework (Pinder, Davids, et al., 2011b) assesses the degree to which experimental and practice tasks simulate key features and coordination demands required in competition performance (Krause, Farrow, Buszard, et al., 2019). Theoretical underpinnings of RLD include concepts from ecological dynamics (e.g., ecological psychology) (Gibson, 1979) and representative design (Brunswik, 1956).

2.2.1 Ecological dynamics

When individuals interact or move with respect to their surrounding environment, they have opportunities to change or modify their actions by detecting and using information uniquely related with environmental properties of interest (Araújo, 2007). Ecological dynamics provides an explanation of how individuals exploit available sources of information in order to adapt or regulate their actions (Davids et al., 2012; Davids, Araújo, Seifert, & Orth, 2015; Gibson, 1979). This integrated approach samples ideas from ecological psychology and dynamical systems theory (Araújo et al., 2006; Davids et al., 2012). Further, it addresses weaknesses in traditional practice approaches associated with expert sport performance, which tend to focus on the performer and environment separately (Araújo & Davids, 2011; Araújo et al., 2006; Seifert & Davids, 2017).

2.2.1.1 Ecological psychology

Ecological psychology considers the importance of a synergetic relationship between an organism (i.e., performer) and the surrounding environment (Dicks, Davids, & Araujo, 2008). This implies that a true understanding of human movement and behaviour can only be gained through the consideration of a performer's natural environment. James Gibson (1979) introduced the theory of visual perception, which hypothesised that the environment contains context-specific opportunities for action, called affordances, and the performer's perceptions of the environment become information for action (Davids, Button, & Bennett, 2008; Fajen, Riley, & Turvey, 2009; Renshaw, Davids, Shuttleworth, & Chow, 2009).

The concept of affordances is central to the ecological theory and includes two key facets: (i) the environment in and of itself is meaningful and (ii) the performer's perception of the environment consists of opportunities for action (Withagen, De Poel, Araújo, & Pepping, 2012). While the performer's perceptual interpretation of the environment becomes information to drive movements, movement decisions also influence the type of information picked up by the performer (Renshaw et al., 2009). For example, the multi-articular action in swimming causes changes to the fluid flow. In turn, this provides new perceptual information about the aquatic environment (Guignard, Rouard, Chollet, Ayad, et al., 2017; Guignard, Rouard, Chollet, Hart, et al., 2017; Seifert et al., 2013; Wei, Mark, & Hutchison, 2014). In the same way, changes in fluid flow conditions may also alter movement responses or offer new opportunities to interact with the surrounding environment (Guignard, Rouard, Chollet, Hart, et al., 2017; Renshaw et al., 2009). As such, swimmers have opportunities to make functional movement decisions in a landscape of continuously changing affordances (Gibson, 1979; Guignard, Rouard, Chollet, Hart, et al., 2017).

Functional movement solutions, within the ecological paradigm, involve the continuous coupling between perception and action (Gibson, 1979). A given environment may afford different sources of information to act upon, yet functional movement solutions are also reliant on the performer's expertise and aptitude for picking up different sources of information (Davids et al., 2008; Fajen et al., 2009; Pinder, Davids, et al., 2011a; Withagen et al., 2012). For instance, while there is a metaphorical landscape of affordances within any given environment, only a select few may be appropriate for a given context (Hristovski, Davids, Araújo, & Button, 2006). Selecting the most appropriate affordances is dependent on the performer's understanding of the environment and skill level (Bruineberg & Rietveld, 2014). Skilled performers adapt better by interacting task and environmental constraints, allowing more consistent performance outcomes to be achieved (Davids et al., 2003). It is therefore important that training tasks adequately sample relevant constraints in order to provide performers with opportunities to practice attuning to and selecting appropriate affordances (Araújo et al., 2015; Araújo et al., 2006; Araújo et al., 2007; Gibson, 2014).

2.2.2.2 Dynamical systems theory

Dynamical systems theory recognises humans as complex neurobiological systems with self-organised functional behaviours able to move and coordinate different body parts in response to perceived affordances and changing constraints of the environment (Davids et al., 2015; Davids et al., 2008; Kelso, 1995). Key ideas from dynamical systems theory are that non-linear behaviour tendencies exist, meaning that behaviour can be stable or unstable, and sub-systems have the ability to influence or compensate for other system components (Chow, Davids, Hristovski, Araújo, & Passos, 2011; Davids et al., 2008; Seifert, Komar, Araújo, & Davids, 2016). This approach challenges traditional views of movement variability, which assumes that variability should be eliminated and proposes that variability can instead be functional to movement coordination behaviours (Bartlett, Wheat, & Robins, 2007).

Functional behavioural and movement coordination patterns emerge through a process of self-organisation shaped by interacting constraints and environmental conditions (Bernstein, 1967; Davids et al., 2008). To fulfil a task goal, many redundant degrees of freedom within the human neuro-skeletomuscular apparatus are capable of interacting to produce infinite patterns of coordination (Bernstein, 1967; Davids, Handford, & Williams, 1994; Kelso, 1995; Seifert et al., 2016). This exhibits degenerate behaviours which demonstrates the human ability to vary movement coordination behaviours to produce the same function or yield the same output (Seifert et al., 2016). Therefore, depending on the sport, functional movement consistency may not necessarily require movement pattern consistency (Bartlett, 2014; Davids et al., 2003; Phillips, Davids, Renshaw, & Portus, 2010).

In freestyle, swimmers continually change the depth, orientation, shape, medial-lateral displacement and velocity of the hand during the underwater phases of the stroke (Bilinauskaite, Mantha, Rouboa, Ziliukas, & Silva, 2013). Even though swimmers must continuously adapt to interacting constraints during race-pace swimming, Sanders, Button, and McCabe (2019) found minimual inter-trial variability of the wrist (hand) path during 25 m freestyle sprints. It is assumed that the consistency of the hand path is a result of effective compensation through functional variability of segmental and joint contributions across other variables such as shoulder roll. As such, skilled individuals are able to search for functional movement solutions, in response to performance environment uncertainties, to achieve the same task goal (Davids et al., 2012).

Within a neurobiological system, coordinated patterns that are functional and stable are referred to as attractors (Davids et al., 2008; Kelso, 1995; Warren, 2006). The stability and consistency of behaviour can be strengthened through learning environments and unpredictable constraints that create a repertoire of movement attractors to be developed (Chow, Davids, Button, & Koh, 2008; Davids et al., 2012; Davids et al., 2008; Headrick, Renshaw, Davids, Pinder, & Araújo, 2015). In the swimming setting, the dive start requires a large amount of functional practice over an extended time frame to allow the swimmer to achieve fast, consistent and efficient performance outcomes. Control parameters are defined as informational variables that guide a system between different states of organisation (Hristovski et al., 2006; Kelso, 1995). A control parameter in the swimming dive example could be the position of the adjustable, angled, back footrest on the start block. Also, a control parameter could be perceptual information about the aquatic environment. It is important that the constraints impinging on individuals are understood by sport scientists and coaches, as minute changes to a control parameter can significantly affect behaviour and movement dynamics (Hristovski et al., 2006).

2.2.2 Constraints

Functional behavioural patterns that emerge in a performance context are dependent on the existing environmental conditions and a range of constraints that shape their behaviour (Davids, 2010). Constraints, in this context, are boundaries or features that promote or limit movement and are typically classified into three core categories: organismic, environmental and task (Kelso, 1995; Newell, 1986; Newell, Broderick, Deutsch, & Slifkin, 2003). Organismic or individual constraints refers to the personal characteristics of individuals, such as their gender, age and physical (e.g., anthropometric) properties, which precludes the performance of skill. For example, one swimmer may have a quicker freestyle swimming speed than another swimmer due to having a larger hand area, foot size, height, or more efficient technique (Seifert, Button, et al., 2010; Seifert et al., 2013).

Environmental constraints are generally recognised as time independent and external to the individual (Davids et al., 2008; Davids, Jia Yi, & Shuttleworth, 2005; Newell, 1986; Seifert et al., 2013; Seifert & Davids, 2017). From a swimming perspective, these may include the temperature or density of the water, surface waves caused by neighbouring swimmers and/or crowd noise (Seifert, Button, et al., 2010; Seifert & Davids, 2017). Task constraints typically pertain to the properties of the activity performed, such as goals of a specific task, sporting rules, game situations/boundaries, instructions given and/or equipment used (Newell, 1986; Seifert, Button, et al., 2010). It has also been suggested that freestyle race-pace, swimming velocity, stroke rate and stroke length may represent task constraints that serve as control parameters in arm coordination transitions (Seifert, Chollet, & Rouard, 2007).

The constraints-led perspective (Newell, 1986) highlights how, through the dynamic interaction of constraints during goal-directed activities, a learner will self-organise in an attempt to generate functional movement solutions (Renshaw et al., 2010; Renshaw, Davids, Newcombe, & Roberts, 2019). However, the relative contribution each constraint has on shaping how the individual organises their many degrees of freedom to produce functional movement patterns is dependent upon the performance context specificities (Glazier & Davids, 2009; Oppici, Panchuk, Serpiello, & Farrow, 2017). While sport practitioners and coaches have begun to adopt a ‘constraints-based’ approach to improve the design of practice tasks, an appropriate understanding of how constraints influence the perception-action process involved in movement development is also required (Chow, 2013; Davids et al., 2008; Renshaw et al., 2019).

The manipulation of various constraints can shape and promote adaptive behaviours (Seifert et al., 2013). In swimming, variations in aquatic resistance and swimming velocity influence the level of environmental constraint the swimmer experiences; yet wearing a race swimsuit (task constraint) can artificially decrease the effect (Seifert, Button, et al., 2010). Verbal instructions; swimming with pacing lights, a frontal snorkel, a kick board, hand paddles, fins, a stretch cord, a parachute (i.e., resistance swimming), or swimming at an imposed stroke rate as dictated by a metronome are a few examples of how constraints can be manipulated in swimming (Gourgoulis, Aggeloussis, Vezos, & Mavromatis, 2006; Gourgoulis et al., 2010; Seifert, Chollet, & Rouard, 2007; Seifert et al., 2014; Telles, Barbosa, Campos, & Júnior, 2011). Tethered swimming where the individual is attached to the pool wall by a cable/cord and must maintain their swimming position is another example of the manipulation of the swimmer's environment and task (Gourgoulis et al., 2010; Guignard, Rouard, Chollet, Hart, et al., 2017). This exercise causes an artificial resistance to the individual, which, in turn, induces temporal behavioural modification to the swimming stroke compared to swimming freestyle normally (Guignard, Rouard, Chollet, Hart, et al., 2017). Swimming on a tether changes inter-limb coordination and increases the time spent in the propulsive phases of the stroke.

A challenge within the constraints-led approach is determining and designing relevant practice tasks to ensure swimmers extend or reinforce their adaptive functional behaviours to dynamical instabilities experienced in the performance environment (Chow, 2013; Guignard, Rouard, Chollet, Hart, et al., 2017; Renshaw, 2010). Manipulation of swimmer movements by adding resistance ensures that information-movement couplings relevant to the performance context are maintained in the learning environment. It also invites swimmers to explore a new coordination pattern or to maintain the current coordination pattern as long as possible (Seifert et al., 2014).

2.2.3 Representative learning design

Representative design is a term originally introduced by ecological psychologist, Egon Brunswik (1956), as a means to highlight the importance of investigating organism-environment interactions. Brunswik's theory advocated that conditions in experimental tasks need to sample stimuli from the organism's natural environment in order to preserve the behavioural context to which the results are intended to be generalised (Araújo & Davids, 2009; Araújo et al., 2007; Dhami, Hertwig, & Hoffrage, 2004). Closely aligned to the experimental design philosophy of representative design is James Gibson's (1979) theory of visual perception, which emphasises that performers share a tight coupling of perception and action with their environment (i.e., information drives movement, which further informs the actions of a performer). In order to consolidate the application of both ecological psychology (Gibson, 1979) and representative design (Brunswik, 1956), RLD was developed (Pinder, Davids, et al., 2011b). RLD is a principled framework used by coaches, sport scientists and researchers to assess the extent to which the key information available within the practice tasks designed are representative of the specific performance context they are attempting to simulate (Krause, Buszard, Reid, Pinder, & Farrow, 2019).

Central to RLD is ensuring that: (i) information variables are sampled from the individual's typical environment and (ii) practice tasks deliver functional couplings between perception and action processes (Davids, Araújo, Vilar, Renshaw, & Pinder, 2013; Pinder, Davids, et al., 2011b). Consequently, training tasks that are more representative of the performance setting have been suggested to produce learning outcomes that can be applied in competition, therein enhancing performance (Vilar et al., 2012). To help guide the assessment of practice task representativeness, RLD proposes the consideration of two key terms: functionality and action fidelity (Pinder, Davids, et al., 2011b; Pinder, Renshaw, Headrick, & Davids, 2013). Understanding both the functionality and action fidelity of the practice design ensures that the complexities of performance and the coupling between key intention, perceptual and action processes are maintained (Pinder et al., 2013).

Functionality refers to the degree to which a performer can regulate their decisions and movement solutions to achieve a similar level of success in the practice environment with comparable information sources (i.e., visual cues) present in the competition environment (Davids et al., 2013; Pinder, Davids, et al., 2011b). The use of a swimming flume to artificially amplify drag (Guignard, Rouard, Chollet, Hart, et al., 2017) is likely to reduce the functionality of the task as information-movement couplings relating to the competition environment are significantly altered (Krause et al., 2018). Specifically, in a flume the water flows in a forward direction over the swimmer and this can change the swimmer's perception of the water flow on propulsive areas (i.e., hands and forearms). Consequently, this can decrease a swimmer's glide duration at the point of hand entry into the water compared to swimming in a pool (Espinosa, Nordsborg, & Thiel, 2015; Guignard, Rouard, Chollet, Hart, et al., 2017). Therefore, the specific context of information available to the swimmer must be considered when assessing the functionality of practice tasks (Pinder, Davids, et al., 2011b).

Complementary to the concept of functionality is action fidelity, which describes the similarity between movement behaviours (e.g., spatiotemporal kinematics) in a reference situation (e.g., competition) and movement behaviours in the experimental or simulated situation (e.g., practice) (Araújo et al., 2007; Pinder et al., 2013; Stoffregen, Bardy, Smart, & Pagulayan, 2003). The fidelity of the action response can be measured by analysing the task performance (e.g., time taken to complete task, joint kinematics data) in both the practice task and actual performance context (Araújo et al., 2007; Travassos et al., 2012). Action fidelity is said to be high when an athlete's behavioural (e.g., actions or decisions) and movement (e.g., spatiotemporal kinematics) responses are the same in training as in competition performance (Pinder, Davids, et al., 2011b). The higher the action fidelity between a training drill and competition, the higher the transfer of skill (Araújo et al., 2007; Davids et al., 2013). For instance, diving into foam pits instead of water altered movement kinematics to low fidelity behaviour as the dive was decomposed and athletes landed feet first rather than wrist first (Barris, Davids, et al., 2013). In tennis, the prescription of the overhand throw practice drill, to infer transfer to the service action, demonstrated low action fidelity as upper body kinematics differed significantly to the original service action (Reid et al., 2015). Together, these findings suggest that, because of the decoupling between perception and action opportunities during the practice tasks, athletes attune to information sources and develop less functional movement responses for performance during actual competition.

The RLD framework ensures the representativeness of practice and experimental design. However, creating representative tasks that satisfy all objectives of the training session may require a higher level of coaching or teaching expertise to balance physiological needs with skill needs (Farrow, Pyne, & Gabbett, 2008; Pinder, Headrick, & Oudejans, 2015). To help coaches better evaluate the representativeness of practice design, the 'representative practice assessment tool' (RPAT) was developed and validated as an applied assessment tool in tennis (see Krause et al. (2018) for full details). Practice activities that promote the perceptual, cognitive and motor demands evident in competition can be considered 'highly representative' (e.g., suited time trial in swimming), whereas those tasks that decouple the demands of competition can be considered ‘lowly representative’ (e.g., drill-based practice) (Ford et al., 2010; Krause et al., 2018). Moreover, to promote functional learning and transfer of skills, this thesis advocates that practice tasks should be designed to offer athletes opportunities to perceive and act as they would during competition. Therefore, current practice design will be critiqued using theoretical underpinnings of RLD.

2.3 Current practice approaches in swimming

Coaches, sport scientists and researchers are on a continual quest to understand what the critical practice requirements are for an athlete to reach (and maintain) elite levels of performance. To gain a better understanding of the extent skill acquisition principles have been translated into practice, researchers have explored the experiential knowledge and practice prescriptions of elite coaches (Greenwood, Davids, & Renshaw, 2012, 2014). Interview data from elite coaches from track and field, gymnastics and cricket revealed that the coaches’ experience-based intuitions often complemented the empirical research (Greenwood et al., 2012, 2014). Namely, coaches expressed ideas consistent with recent knowledge of perception-action coupling and constraints-led approach in the design of training programs.

Observations of elite swimming training have revealed that coaches emphasise principles of deliberate practice within their training programs where they strive for repeatable execution of technique (Junggren et al., 2018). The priority coaches place on these practices is indicative of the importance they place on time spent in specific technical practice from an early age (Côté & Gilbert, 2009; Ericsson et al., 1993; Junggren et al., 2018). In contrast, experiential data drawn from elite coaches in rugby league (Rothwell, Stone, Davids, & Wright, 2017) and field hockey (Slade, Button, & Cochrane, 2015) provide support for representative game scenarios where players draw on other sports experiences and learn to regulate and adapt their performance actions (Araújo & Davids, 2015). While both practice approaches seek to train the athletes in a manner that ensures transfer of learning to competition, a fundamental philosophical difference exists in relation to the relative importance the coach places on how the athletes execute their skills. Swimming coaches follow a traditional biomechanical optimisation model and strive for execution of the same action repeatedly. Whereas the rugby and hockey coaches are more aligned with contemporary skill acquisition approaches and encourage their athletes to develop adaptable movement patterns.

The training observations and coach interviews from swimming coaches have illustrated that during most training sessions, particularly during the warm-up, athletes spend time in drill-based practice tasks (Junggren et al., 2018; Neiva, Marques, Barbosa, et al., 2014; Neiva, Marques, Fernandes, et al., 2014). Drill-based practice tasks are favoured by coaches as they are believed to help achieve ‘perfect’ swimming technique, which supposedly promotes greater swimming efficiency and mechanical consistency (Lucero, 2015). Further, during such practice tasks, athletes supposedly find it easier to explicitly focus on a single movement requirement and this, consequently, elicits greater in-task performance and confidence (Handford, Davids, Bennett, & Button, 1997; Renshaw et al., 2009).

The effectiveness of prescribing practice tasks that promote the development of movement consistency is under debate (Davids et al., 2008; Seifert et al., 2014). Instead, variability in movement patterns can be viewed as a key facet of expert performance (Bartlett et al., 2007; Davids et al., 2003). Consequently, over practicing in drill-based tasks could contribute to undesirable movement outcomes and may pose significant implications for learning (Barris, Davids, et al., 2013; Pinder, Renshaw, & Davids, 2009; Reid, Whiteside, Gilbin, & Elliott, 2013).

Popular types of drill-based tasks include breaking tasks into smaller components (Davids, Kingsbury, Bennett, & Handford, 2001; Ford et al., 2010; Renshaw et al., 2010; Travassos et al., 2012). This is commonly referred to as task decomposition or part-task practice. Drill-based tasks can also be prescribed within block practice where one skill is repeatedly practiced or progressed from basic coordination to the full movement (Brady, 1998, 2008; Porter & Magill, 2010; Williams & Hodges, 2005; Wright & Shea, 2001). Additionally, in swimming, drill-based tasks may also be prescribed with the goal to exaggerate or contrast the stroke movement (Lucero, 2015). This thesis will focus on firstly understanding the type of drill-based tasks prescribed by elite swimming coaches Australia. This information can ensure that the testing protocol used to biomechanically assess common freestyle practice drills is representative of the execution of drills in the training environment.

2.3.1 Practice structure

The sequencing of skill practice can be structured in a blocked or random manner under constant or variable conditions (Williams & Hodges, 2005). The contextual interference effect is a well-established research practice construct, which outlines how practicing multiple variations of the same skill and/or changing between different skills in the same practice tasks may reduce performance in practice yet promote skill learning and transfer (see Brady (1998, 2008)). Drill-based practices tend to focus on improving one specific skill by repetitively practicing that one skill in large blocks without incorporating any other skills (Buszard, Reid, Krause, Kovalchik, & Farrow, 2017). Blocked practice with low contextual interference seems to lead to better performance during the acquisition of the skill in the practice. However, random or variable practice conditions are thought to help athletes better develop attunement to specific perceptual variables as well as coordinate movement patterns accordingly (Brady, 1998; Davids et al., 2008; Renshaw et al., 2009).

Coaches tend to naturally incline towards ensuring that the athlete has made improvement in a particular aspect of the skill being focused on before progressing to a more complex skill (Williams & Hodges, 2005). In this context, skill progression refers to the learning and development of skills from basic performance to more complex movement coordination (Irwin, Hanton, & Kerwin, 2005). While the ecological perspective leans towards creating practice tasks and environments that enable adaptive movement behaviours, there is a threshold whereby excessive variation could subsequently hinder learning. Accordingly, training programs should be individualised to the athlete's skill level and it is suggested that learning is better facilitated when task variations are gradually increased as the athlete's skill level increases (Hodges, Edwards, Luttin, & Bowcock, 2011; Saemi, Porter, Ghotbi Varzaneh, Zarghami, & Shafinia, 2012). The specificities of practice tasks remain underrepresented in swimming and warrants exploration in this thesis.

2.3.2 Task decomposition

In an effort to reduce performance complexities and allow the athlete to achieve a desired level of success, coaches will often decompose or 'break down' a more complex skill into smaller, less complex components (Davids et al., 2001; Davids, Renshaw, Pinder, Greenwood, & Barris, 2017; Magill, 2007). The theoretical bias of task decomposition is to improve the consistency of each smaller skill component so that when incorporated back into the full skill, consistency gained in each part is visible in the skill itself (Davids et al., 2003). For example, in swimming, coaches often prescribe the single-arm drill to allow the athletes to focus on breath timing and body alignment (Arellano et al., 2010;

Lucero, 2015). However, there is no empirical evidence to suggest that breath timing and body alignment, supposedly practiced during the single-arm drill, positively represents the full freestyle stroke in competition.

Previously mentioned, studies in diving (Barris, Davids, et al., 2013) and tennis (Reid et al., 2015; Reid, Whiteside, & Elliott, 2010) have explored the biomechanical effects task decomposition can have on performing the full skill. Using tennis as a case point, Reid et al. (2010) compared movement kinematics between a full tennis serve and two commonly prescribed drills that decompose the tennis serve. The drills included: (i) the 'shadow swing' which involved rehearsing the racquet swing independent of the ball toss and (ii) the rehearsal of the ball toss independent of the racquet swing. Movement kinematics during the rehearsal of the ball toss independent of the racquet swing drill indicated that the ball toss height and average peak rotation were significantly higher than during the full tennis service. This suggested that players tossed the ball differently and applied more force on the ball during that particular drill. The 'shadow swing' drill showed similarities in racquet trajectory during the early swing position compared to the full tennis serve. Reid et al. (2010) also reported an overall lower racquet low point suggesting less trunk and lower limb involvement when using the 'shadow swing' drill. The findings support the notion that for skills that are highly complex (i.e., numerous active degrees of freedom to be coordinated) and highly organised (i.e., movement responses dependent on each other) practicing part of the skill in isolation can significantly change key characteristics of the skill not representative of when performed as a whole in competition (F. E. Fontana et al., 2009; Magill, 2007; Naylor & Briggs, 1963).

Alternatively, it is proposed that coaches implement processes that simplify the task by maintaining information-movement relations instead of coaches prescribing tasks that decompose the skill (Seifert et al., 2013). This can be achieved by adding task constraints or manipulating the relationship that exists between an athlete, their opponent and fellow teammates (Travassos et al., 2012) (as detailed in subsection 2.2.2, p. 16). In swimming, the use of hand paddles or fins is an example of how the propulsive surfaces of the swimmer is increased to help improve hand positioning rather than correcting the technique through task decomposition (Seifert et al., 2013; Seifert, Chehensse, Tourny-Chollet, Lemaitre, & Chollet, 2008).

Swimming coaching textbooks advocate the use of task decomposition or drill-based practice tasks to isolate aspects of the stroke technique in order to reduce movement variability (Guzman, 2007; Lucero, 2015; Maglischo, 2003). While such practice prescriptions may facilitate learning during early movement development, repeatedly practicing a subsection of the stroke in isolation decouples inter-limb coordination and movement timing (Arellano et al., 2010; López et al., 2002). Routine use of task decomposition methods is predicted to hinder, rather than promote, the development and transfer of the skills required during competition performance (Davids et al., 2001; Reid et al., 2010; Renshaw, Oldham, Davids, & Golds, 2007). To date, there are only two empirical research outputs from conference and symposium proceedings that have investigated the immediate effects of swimming drills that decompose the stroke into component parts (Arellano et al., 2010; López et al., 2002). This calls for further and more in-depth assessments of commonly prescribed task decomposition swimming drills from both a biomechanics and learning processes perspective. As such, the action fidelity of commonly prescribed swimming practice drills will be assessed throughout this thesis using underpinnings of RLD.

2.4 Biomechanical components of freestyle technique

The way swimmers coordinate the complex multi-articular actions of swimming is of particular interest to researchers as the aquatic environment highly constrains movement (Guignard, Rouard, Chollet, Hart, et al., 2017; Pendergast et al., 2005; Simbaña-Escobar, Hellard, & Seifert, 2018). The kinematics and kinetics of freestyle swimming are the most studied of the swimming stroke as freestyle is the fastest and most effective form of locomotion through the aquatic environment (McCabe et al., 2011; Sanders, Gonjo, & McCabe, 2016; Seifert, Boulesteix, et al., 2005; Skorski et al., 2014). However, there is very little evidence supporting how current drill-based practice tasks help to develop these features. In order to assess the effect of drill-based practice tasks on freestyle kinematics, biomechanical fundamentals related to efficient and fast freestyle technique will be assessed in the subsequent sections.

2.4.1 Drag

The aquatic environment causes the greatest resistance to the cyclic swimming movement as the water's density ($\rho_{water} = 1000\ kg/m^3$) is 800 times denser than air and viscosity ($\mu_{water} = 8.9 \times 10^{-4}$) is 50 times greater than air (di Prampero & Osgnach, 2019; Guignard et al., 2019; Guignard, Rouard, Chollet, & Seifert, 2017). Swimming speed, as with all forms of human locomotion, can be improved by either increasing propulsive forces through the water or by decreasing resistive forces, also referred to as drag (Gatta, Cortesi, Fantozzi, & Zamparo, 2015; Toussaint, 2002; Toussaint & Beek, 1992). Drag can be categorised in two ways: passive and active drag (Bixler, 2005). Passive drag is the hydrodynamic resistance generated when a swimmer is in a fixed or streamline position (Naemi, Easson, & Sanders, 2010; Narita, Nakashima, & Takagi, 2018; Webb et al., 2011). Active drag refers to the resistance created during swimming such as leg kicking and arm stroking (Narita, Nakashima, & Takagi, 2017; Narita et al., 2018).

When a swimmer moves at the surface of the water, drag forces emerge in the direction opposite to the line of movement (Bixler, 2005; Toussaint, Van Den Berg, & Beek, 2002). While total drag (F_d) during swimming is still not fully understood and continues to be investigated (Narita et al., 2017), it has been distinguished into three general components: friction drag (or 'skin drag') (F_f), pressure drag (or form drag) (F_P) and wave drag (F_w) (Janssen, Wilson, & Toussaint, 2009; Toussaint et al., 1988; Toussaint, Seifert, & Chollet, 2011) (Equation 2.1).

$$F_d = F_f + F_P + F_w \qquad [\mathbf{2.1}]$$

Frictional drag represents the forces acting tangential to the surface of the moving swimmer (Guignard, Rouard, Chollet, Hart, et al., 2017; Toussaint et al., 1988). The magnitude of frictional drag experienced is dependent on the wetted surface between the swimmer's skin and the flow of water molecules in contact with the skin, known as the boundary layer, and how these molecules behave (Ungerechts & Arellano, 2011). The boundary layer is distinguished into laminar, turbulent, or transitional flow around the body (Toussaint et al., 2011). In a laminar boundary layer regiment, there is no exchange between flowing layers (Ungerechts & Arellano, 2011). A boundary layer with a turbulent flow produces the highest frictional drag. The speed and location of these turbulences are dependent on the size and speed of the swimmer. They are also dependent on the density and viscosity of the water (Maglischo, 2003; Toussaint et al., 2011). Transition from laminar to turbulent boundary layers depends on the surface roughness, amount of initial turbulence and how quickly pressure and velocity change along the length of the boundary layer (Bixler, 2005). Swimmers tend to 'shave down' before major competitions in an attempt to reduce the effect of frictional drag (Sharp, Hackney, Cain, & Ness, 1988).

Form drag is the result of differences in pressure caused by boundary layer separation from the frontal and rear areas of the body (Bixler, 2005; Ungerechts & Arellano, 2011). As the name implies, form drag is dependent upon the shape or form of the swimmer (Bixler, 2005). It contributes the most to overall total drag during swimming but largely depends on the flow conditions outside of the boundary layer (Ungerechts & Arellano, 2011). When water particles move along the swimmer's body, they are slowed down as a result of skin friction (Naemi et al., 2010). Boundary layer separation then occurs when the momentum of the water in the boundary layer cannot follow the shape of the body, causing a relatively low-pressure region behind the body called the 'wake' (Naemi et al., 2010). Thus, a smaller frontal area causes a smaller flow of water in the wake, resulting in a smaller total drag (Ungerechts & Arellano, 2011). Having the head above water during certain freestyle training tasks or drills increases form drag as the swimmers' frontal/cross sectional area is larger than when in the streamlined body position (Naemi et al., 2010; Toussaint & Beek, 1992; Zamparo & Falco, 2010).

Swimming near the surface of the water creates the formation of waves and generates wave drag (Toussaint, Roos, & Kolmogorov, 2004; Ungerechts & Arellano, 2011). To increase swimming speed, swimmers' arms and legs tend to move at higher frequencies, which causes an augmented effect on active wave drag (Toussaint et al., 1988). Changes in swimming speed not only directly influence the level of aquatic resistance but also change inter-arm freestyle coordination (Seifert et al., 2015). Manipulating components of drag forces experienced by the swimmers might induce disruptions to the fluid flows and provoke positive adaptations in swimming behaviours (Guignard, Rouard, Chollet, Hart, et al., 2017). Swimming in a flume, tethered or with a parachute, are methods used to amplify drag (Guignard, Rouard, Chollet, Hart, et al., 2017). However, coaches and sport scientists need to be aware of the potential consequences associated with the manipulation of constraints (Telles et al., 2011). As previously exemplified, in a flume the water flows in a forward direction over the swimmer and this can change the swimmer's perception of the water flow on propulsive areas, which can alter coordination parameters of the stroke and decrease a swimmer's glide duration at the point of hand entry into the water compared to swimming in a pool (Espinosa et al., 2015; Guignard, Rouard, Chollet, Hart, et al., 2017).

2.4.2 Propulsion

Propulsion is generated by applying forces to the water in order to drive the swimmer forward (Counsilman & Counsilman, 1994; Guignard, Rouard, Chollet, Hart, et al., 2017). However, when moving through the water, resistive forces are created by the differences in pressure between the frontal and posterior surface of the hand (or body) (Counsilman & Counsilman, 1994; Guignard, Rouard, Chollet, Hart, et al., 2017). As such, propulsion is the resultant of two resistive forces known as drag and lift (Bixler, 2005; Maglischo, 2013). Drag always points in the direction opposite to the line of movement (Bixler, 2005; Toussaint et al., 2002). Lift, on the other hand, is the force component perpendicular to the direction of drag (Rushall, Sprigings, Holt, & Cappaert, 1994; Toussaint et al., 2002).

It would be incorrect to state that swimming performance is solely dependent on the interaction of propulsive forces and resistive forces without considering the mechanical power produced by the swimmer (Toussaint et al., 2011). Only a portion of the total mechanical energy delivered is used beneficially for propulsion and to overcome drag, as some of the mechanical power generated by a swimmer is expended in giving water a kinetic energy change (Berger, Hollander, & De, 1997; Toussaint & Truijens, 2005). For this reason, the total mechanical power delivered by a swimmer, minus internal losses of mechanical power, can be discerned as power used beneficially to overcome drag (Toussaint & Truijens, 2005). Accelerating small masses of water at high velocity is noted to lead to lower efficiency than accelerating larger masses of water, per unit of time, at a low velocity (Guignard, Rouard, Chollet, Hart, et al., 2017). Swimming velocity is, therefore, dependent on the generation of propulsive forces necessary to match the hydrodynamic drag forces produced by the forward moving body (Barbosa et al., 2010; Ribeiro et al., 2013; Toussaint & Beek, 1992).

2.4.3 Swimming parameters

At the elite level in swimming, key performance parameters are measured in training and competition. It is important to monitor these parameters as marginal adjustments can potentially increase or decreases an athlete's level of success (Barbosa, Fernandes, Keskinen, & Vilas-Boas, 2008). For analysis, swimming parameters are generally broken into four specific segments: start, turn, finish and free-swimming (Mooney, Corley, Godfrey, Quinlan, & ÓLaighin, 2015). The start is defined as the time taken from the starting signal to when the centre of the swimmer's head reaches the 15 m mark and is typically divided into three phases: on-block, flight and underwater (Cossor & Mason, 2001; Elipot, Dietrich, Hellard, & Houel, 2010b; Tor, Pease, & Ball, 2014). The turn is defined as the time from when the centre of the swimmer's head reaches the 5 m mark before the wall to 10 m after the wall (Cossor, Blanksby, & Elliott, 1999; Slawson, Conway, Justham, Le Sage, & West, 2010; Slawson, Conway, Justham, & West, 2010). Phases within the turn include the approach to the wall, the turn or rotation to reorient the body in preparation for swimming the next lap, the push-off or wall contact, the glide phase and the stroke preparation (Chakravorti, Slawson, Cossor, Conway, & West, 2012; Slawson, Conway, Justham, Le Sage, et al., 2010). The finish is referred to the last 5 m before the swimmer's hand touches the wall at the end of the race. Free-swimming describes the regular swimming performance during each lap that occurs outside the turn, start and finish segments (Mooney, Corley, Godfrey, Quinlan, et al., 2015). Within the four specific swimming segments, different categories of analysis can take place through the measurement of either temporal, kinematic, or kinetic variables (see Table 2.1, modified from Mooney, Corley, Godfrey, Quinlan, et al. (2015)).

Table 2.1 Parameters relating to each category of analysis per swimming segments.

Swimming segments	Categories of analysis	Parameter(s)
Start Turn Finish Free-swimming	Temporal	Start, turn and finish times
		Free-swimming lap times
	Kinematic	Arm stroke length (SL)
		Arm stroke and leg kick rate/frequency (SF)
		Arm stroke and leg kick count
		Arm stroke velocity (mean)
		Segmental kinematics - joint or segment angles, pitch and roll angles, amplitude, displacement
	Kinetic	Arm or leg wall push-off force
		Torque
		Impulse at the wall push-off

Note: This is not an exhaustive list of measurable swimming parameters or possible categories of analysis. For example, inter limb coordination can be measured via temporal and/or kinetic methods of analysis (Formosa, Sayers, & Burkett, 2013, 2014a, 2014b).

Key performance parameters relating to a swimmer's free-swimming speed, over a given distance, are stroke length (SL) and stroke rate (SR) (Seifert, Boulesteix, et al., 2005). The distance travelled by the body during a complete stroke is defined as SL. The number of stroke cycles per minute is the definition of SR. Swimming speed is average horizontal velocity of the swimmer. Swimming speed, SL and SR have been used to examine skill and swim performance in competition (Chollet, Delaplace, Pelayo, Tourny, & Sidney, 1997; Mason & Cossor, 2000). Stroke index (SI) is also used to assess swimming ability and is determined as the product of SL and swimming velocity (Sánchez & Arellano, 2002). It has been argued that these performance parameters alone do not provide a complete picture of swim performance (Seifert, Chollet, et al., 2004). Investigating certain segment kinematics (see Table 2.1), in addition to the key performance parameters, allows for more comprehensive understanding of the free-swimming technique (Seifert, Chollet, et al., 2004). Kinematic variables associated with increased free-swimming speed and effective freestyle technique will be investigated in the following sections.

2.4.4 Kinematic aspects of freestyle

Technically, in competitive freestyle swimming the swimmer may choose any swimming style other than that of the other three competitive form strokes - breaststroke, backstroke and butterfly ("Fédération Internationale de Nation [FINA]," 2017). Freestyle, also referred to as front crawl, is characterised by alternating overhead arm stroke phases and a number of near-vertical leg kicks (Carmigniani, Seifert, Chollet, & Clanet, 2019; Yanai & Wilson, 2008). In order to evaluate the stroke technique, segmental kinematics are typically divided into upper- and lower-limb coordination strategies or the arm stroke and leg kick, respectively (de Jesus et al., 2016; Deschodt et al., 1999; Mooney, Corley, Godfrey, Quinlan, et al., 2015). The coordination between the upper and lower limbs is challenged in freestyle swimming due to the structurally and functionally different movements between the arms rotating 360° around the shoulder and the near-vertical, pendulum leg kicking action (Guignard et al., 2019; Wannier et al., 2001).

2.4.4.1 Upper-limb kinematics

Forward propulsion in swimming is generated by the coupling of movements between the upper- and lower-limbs. However, the upper-limb actions provide around 68% of the total propulsion, whereas the lower-limbs contribute to around 31% (Morouço, Marinho, Izquierdo, et al., 2015; Swaine et al., 2010). The greater contribution of the upper-limbs to total propulsion has led to extensive research on upper-limb kinematics where the arm stroke cycle is typically categorised into four phases: (i) entry and catch, hand's entry into the water to the beginning of its backwards movement; (ii) pull, the beginning of the hand's backwards movement to its arrival in the vertical plane to the shoulder (constitutes the first part of propulsion); (iii) push, the hand's position below the shoulder to its release from the water (constitutes the second part of propulsion) and (iv) recovery, the hand's release from the water until its re-entry into the water (Chollet et al., 2000; Seifert, Chollet, & Rouard, 2007; Sobrino et al., 2017). The sum of the pull and push arm stroke phases represents the propulsive phase of the stroke (Sobrino et al., 2017).

The hand motion has a direct influence on the streamlined body alignment, generation of propulsion and timing of body segments (Maglischo, 2003; Sanders et al., 2017). In order to effectively generate propulsion, swimmers change the depth, orientation, shape, medial-lateral displacement and velocity of the hand throughout the underwater path of the freestyle stroke (Bilinauskaite et al., 2013). This can be explained via Newton's 3rd Law: "For every action there is an equal and opposite reaction". Worded differently, the swimmer's hand segment pushes the water backwards (pull phase of the stroke), creating a counter-force of equal magnitude that propels the swimmer forward (McCabe, 2008; Toussaint & Truijens, 2005). Further, according to Newton's 2nd Law ($F = m \times a$), the propulsive force (F) generated is determined by the mass (m) and acceleration (a) of the water. The time over which the water is accelerated is also an important consideration, as the change in motion (momentum) of a body is the product of both force and time (McCabe, 2008).

It has been calculated that the hand path of an elite swimmer has taken years of repetitive practice involving more than two million rotations per year (Mountjoy & Gerrard, 2011). For this reason, many studies have investigated the hand path in order to better understand its contribution to propulsion during freestyle (Bilinauskaite et al., 2013; Gourgoulis, Aggeloussis, Vezos, Antoniou, & Mavromatis, 2008; Gourgoulis et al., 2010). Typically, the hand follows either an *S*- or *I*-shaped pattern underwater (Counsilman & Counsilman, 1994; Sanders et al., 2017). While both hand patterns are beneficial to swimming performance, simulations have shown that the *I*-shaped hand path produces larger forces during the pull phase of the stroke. Therefore, the *I*-shaped hand path is typically displayed in sprint-distance freestyle swimmers (Takagi, Nakashima, Sato, Matsuuchi, & Sanders, 2016). The *S*-shaped hand path is preferred by middle- and long-distance freestyle swimmers as less energy is lost to the water despite the smaller force production during the pull phase (Guignard, Rouard, Chollet, Hart, et al., 2017; Sanders et al., 2017; Takagi et al., 2016). Gourgoulis et al. (2010) investigated the medial-lateral displacement of the hand during freestyle swimming with and without added resistance. While there were no effects on the medial-lateral displacement of the hand, the absolute pull length was increased during resisted swimming yet the relative pull length remained unchanged. This indicated that swimmers were able to maintain the same range of hand motion and extension of the elbow in all experimental conditions. Given this, it could be suggested that resisted freestyle positively transfers to competition freestyle technique. However, when it comes to drill-based practice tasks, the effects on the depth and medial-lateral displacement of the hand has not been established in the literature and will be investigated as part of this thesis.

Generally, the propulsive contribution of the other body segments is to enable the hand to move through the water in a path that maximises propulsion without disturbing the horizontal alignment of the body (Sanders et al., 2017). The importance of the 'high' elbow position (greater elbow flexion) during the pull phase of the freestyle stroke is discussed regularly within the literature due to its influence on the hand's trajectory to allow for the generation of propulsive force (Cappaert, Pease, & Troup, 1995; Counsilman & Counsilman, 1994; Nakashima, Maeda, Miwa, & Ichikawa, 2012; Suito, Nunome, & Ikegami, 2017). Elbow flexion and extension utilises the forearm as a long lever to change the hand's trajectory (Figueiredo, Nazário, Cereja, Vilas-Boas, & Fernandes, 2011; Figueiredo, Sanders, Gorski, Vilas-Boas, & Fernandes, 2012). Hence, the elbow angle changes continuously throughout the stroke cycle (McCabe et al., 2011; McCabe & Sanders, 2012). It has been recommended that drills be prescribed to promote a continuously changing elbow angle, although the effectiveness of such drills requires further investigation (McCabe et al., 2011).

2.4.4.2 Lower-limb kinematics

In freestyle, the leg kick, also referred to as "flutter-kick". This kick action is performed through an alternating top and bottom movement of outstretched lower limbs. During the leg kick cycle, the feet are externally rotated and plantarflexed (Gatta, Cortesi, & Di Michele, 2012). The leg kick cycle can be broken down into two successive movement phases. The downward kick which is the time between the highest and lowest point of the foot. This phase is considered the propulsive sequence of the movement. The second movement phase is the upward kick which is the time from the lowest and highest point of the foot during the kicking movement (Andersen & Sanders, 2018; Sobrino et al., 2017). The main kick patterns used in freestyle are either two- four-, or six-beat per arm stroke cycle (Maglischo, 1993). Six-beat kicking consists of three complete leg cycles where the three downward and three upward kick phases are performed on each complete arm stroke cycle (Maglischo, 2003; Sanders & Psycharakis, 2009).

The contribution of the leg kick, to generate propulsive force, is commonly considered secondary to the upper-limb actions (Andersen & Sanders, 2018; Deschodt et al., 1999; Gourgoulis et al., 2014). At high velocities, the contribution of the leg kick is around 31% of the total force and power produced by the swimmer (Morouço, Marinho, Izquierdo, et al., 2015). While the kick does directly provide a large amount of propulsive force (Sanders & Psycharakis, 2009); it is believed that the main function of the leg kick is to stabilize body roll during the arm stroke (Yanai, 2003), maintain a low-resistant horizontal alignment by diminishing the trunk inclination (Counsilman & Counsilman, 1994; Gourgoulis et al., 2014; Sanders et al., 2017) and facilitate a more effective arm action (Deschodt et al., 1999). Overall, these functions of the kick will preserve the streamline body alignment and assist to minimise resistive drag.

The involvement of the trunk on freestyle performance is generally divided into upper- (shoulder) and lower- (hip) trunk motion, as there is some independence between the magnitude of the hip rotation with respect to the shoulder rotation (Psycharakis & Sanders, 2008; Sanders et al., 2017). The inclination of the trunk affects the projected frontal surface area of the swimmer, which amongst other parameters influences the magnitude of resistive drag force acting on the body (Yanai & Wilson, 2008; Zamparo, Gatta, Pendergast, & Capelli, 2009). The increase in swimming speed can reduce trunk inclination, although excessive kicking movements may disturb the horizontal alignment of the swimmer and increase in resistive drag force (Zamparo et al., 2009). During some arm-specific freestyle drills, the leg kick is reduced, which could result in an increase in trunk inclination (Gourgoulis et al., 2014). This thesis will further explore this in the investigation of upper-limb freestyle drills.

2.4.4.3 Arm coordination

Analysing the pattern of coordination between different body segments provides information to better understand how individuals interact with different constraints in order to perform specific movement solutions (Sobrino et al., 2017). In freestyle swimming, aspects of inter-limb coordination have been extensively analysed through the index of coordination (IdC) measure (Chollet et al., 2000; Gourgoulis et al., 2014; Millet, Chollet, Chalies, & Chatard, 2002; Seifert, Chollet, & Allard, 2005). IdC is a non-dimensional, timing-based measure that separates the beginning of the propulsive phase of one arm to the end of the propulsive phase of the other arm as a percentage of the mean duration of the arm stroke cycle (see Chollet et al. (2000) for detailed explanation). Three different coordination patterns have been identified: (i) *opposition*, continuity between the two arm propulsions where one arm begins the pull phase when the other arm is finishing the push phase, IdC = 0%; (ii) *catch-up*, time gap between the propulsive phase of the two arms, IdC < 0% and (iii) *superposition*, overlap between the propulsive phase of the two arms, IdC > 0% (Chollet et al., 2000; Chollet & Seifert, 2011; Gourgoulis et al., 2014; Seifert, Chollet, & Rouard, 2007).

Research has reported that the manipulation of constraints can impact coordination patterns in a way that either supports or deteriorates performance (Chollet et al., 2000; Guignard, Rouard, Chollet, Hart, et al., 2017). As a result, the design of practice tasks needs to allow the individual to learn and perform movement solutions that are either functional for, or representative of, performance in the competitive environment (Barris, Farrow, & Davids, 2014; Davids et al., 2017; Pinder et al., 2015). However, there is no published data on the positive or negative influence specific technique drills have on inter-limb coordination. This thesis will consider inter-limb coordination in the biomechanical assessment of commonly prescribed freestyle drills.

2.4.5 Measurement of swimming parameters

Many significant changes have occurred in competitive swimming since its introduction into the Olympic program in 1896 (Nugent, Comyns, Burrows, & Warrington, 2017). Technological advancements coupled with the increased understanding of swimming biomechanics and fluid mechanics have greatly contributed to current swimming improvements (Barbosa et al., 2008; Counsilman & Counsilman, 1994; Rouard, 2011). Video-based approaches, wearable technologies, computer simulation, robotics, computation fluid dynamics and flumes have aided swimming biomechanical analysis (Sanders et al., 2017). Both two-dimensional (2D) and three-dimensional (3D) video-based analysis have been the most popular methods of monitoring swimming in competition, training and research (Mooney et al., 2016; Sanders et al., 2006; Tor, Ball, Pease, & Hopkins, 2012) More recently, the rapid development of wearable inertial measurement units (IMUs) has offered new possibilities in characterising swimming behaviour (Guignard, Rouard, Chollet, & Seifert, 2017). While the use of IMUs is becoming a popular alternative to video-based analysis, the cost and reliability of these units coupled with other measurement limitations prevents their use in this thesis. The following section details the methodological requirements and considerations required for 3D video-based analysis.

2.4.5.1 Image-based analysis

The Chinese proverb, “A picture is worth more than ten thousand words” holds true in swimming biomechanics. That is, the gold standard method for measuring kinematic stroke parameters involves timing-based measures and manual digitisation of anatomical landmarks from 2D video images (Ceseracciu et al., 2011; Guignard, Rouard, Chollet, & Seifert, 2017; Sanders et al., 2006; Winter, 2009). The specific camera setup required for either qualitative or quantitative analysis is dependent on the purpose of analysis and the swimming parameters under investigation (Mooney, Corley, Godfrey, Os-borough, et al., 2015). Competition analysis typically employs a single camera setup (2D analysis) to measure SL, SR, skill times (start, turn, finish) and mean stroke velocity for each 25 m section of free swimming (Guignard, Rouard, Chollet, & Seifert, 2017; Mason & Cossor, 2000). While this approach provides useful information to evaluate swimming performance, both quantitatively and qualitatively (Mooney et al., 2016), a single 2D camera approach does not allow for the most reliable and accurate quantification of the multi-planar swimming movement (Psycharakis et al., 2005; Sanders et al., 2012). Therefore, from a research and specific technique assessment point of view, the use of a multi-digital camera setup for 3D quantitative analysis is recommended over a 2D camera setup (Sanders, Chiu, et al., 2015). This thesis will utilise a multi-camera setup for the 3D kinematic assessment of commonly prescribed freestyle drills.

Currently, the application of a multi-digital camera setup for 3D analysis is the most widely used method of motion measurement in swimming biomechanics research (de Magalhaes, Vannozzi, Gatta, & Fantozzi, 2014; Elipot, Houel, Hellard, & Dietrich, 2009). The Direct Linear Transformation (DLT) method (Abdel-Aziz & Karara, 1971) allows for the 3D reconstruction of 2D video pixel (u, v) coordinates obtained from manually digitised points (de Jesus et al., 2015). Briefly, the DLT method determines the linear relationship between the 2D video pixel coordinates and the 3D object-space reference frame (Dadashi, Millet, & Aminian, 2013; Payton, 2008) (Equations 2.2 and 2.3).

$$u = \frac{L_1 x + L_2 y + L_3 z + L_4}{L_9 x + L_{10} y + L_{11} z + 1} \qquad [\mathbf{2.2}]$$

$$v = \frac{L_5 x + L_6 y + L_7 z + L_8}{L_9 x + L_{10} y + L_{11} z + 1} \qquad [\mathbf{2.3}]$$

Where *x*, *y*, *z* are the object-space coordinates of the object point; *u*, *v* are the video pixel coordinates of the image point; and L_1 to L_{11} are the DLT parameters (Abdel-Aziz & Karara, 1971; Kwon & Casebolt, 2006).

2.4.5.1.1 Camera lens distortion

The DLT approach is convenient for swimming research as it allows flexibility in regards to the choice of camera type and setup (Payton, 2008). The DLT algorithms (Equations 2.2 and 2.3) are based on a pinhole camera model, which assumes a collinearity condition. A collinearity condition is where a point in the 3D object space is projected by a straight line passing through the projection centre onto the sensor of the camera (Heikkila & Silven, 1997; Rossi, Silvatti, Dias, & Barros, 2015). Figure 2.1 illustrates the components of a pinhole camera model where the camera's focal length is the distance between the centre of projection and the image plane (Sturm, 2014). The projected image is deformed as a result of deviations that light rays suffer whenever passing from the air to the lens and then from the lens back to the air. This is commonly known as lens distortion (Rossi et al., 2015). Lens distortion can be classified into radial and tangential distortion (Brown, 1971; Clarke & Fryer, 1998; Rossi et al., 2015). Radial distortion causes a point in the image to be displaced radially (Kannala, Heikkilä, & Brandt, 2007; Rossi et al., 2015). Tangential distortion results from tilting between a set of lenses and causes the centre of curvature of the lens not to be collinear, which displaces the image coordinates (Kannala et al., 2007; Rossi et al., 2015).

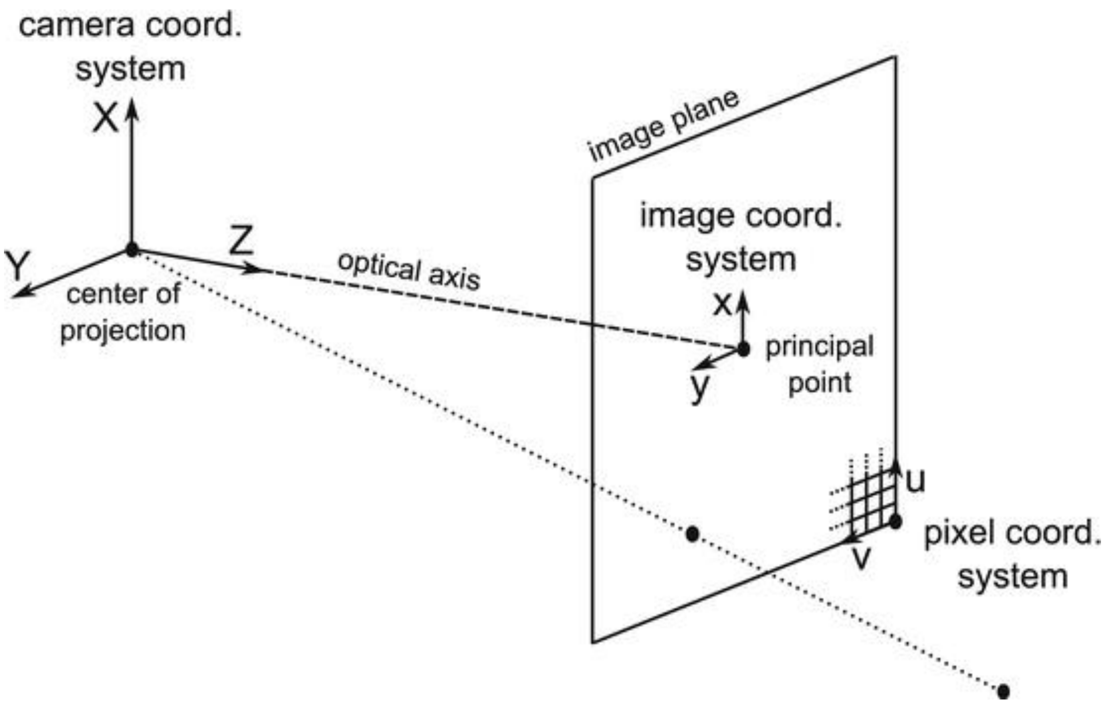


Figure 2.1 Pinhole camera model illustrated by Sturm (2014).

In swimming, specialist underwater cameras have been developed and are available through dedicated manufactures (Mooney, Corley, Godfrey, Os-borough, et al., 2015). The SwimPro camera system (SwimPro®, Newcastle, Australia) is currently the most common underwater camera system used by elite swimming coaches and sport scientists in Australia. Consequently, the SwimPro camera system was used to capture the swimming movement in this thesis. SwimPro cameras have a wide-angle (fish-eye) lens, which causes tangential distortions to the image. If uncorrected, these image distortions can cause inaccurate geometric measurements during data processing (Kannala et al., 2007; Kwon & Casebolt, 2006). The DLT algorithm does not correct the errors caused by lens distortions (Kwon & Casebolt, 2006). Therefore, to improve the accuracy of the DLT algorithm, techniques have been developed to correct the distortion of the image (Zhang, 2000). Zhang (1998) proposed a method of slowly moving a planar chequered board grid, containing squares of known size, in front of the camera. The images of the chequered board grid, placed at different orientations in front of the camera, are then imported into a developed algorithm (available as a MATLAB (MathWorks, Natick, MA, USA) toolbox) in order to obtain the intrinsic camera parameters for each camera separately (Beardsley, Murray, & Zisserman, 1992; Remondino & Fraser, 2006; Silvatti et al., 2013). These parameters include focal length, principal point, radial distortions, tangential distortions and pixel size. After the camera parameters have been obtained, the epipolar geometry and triangulation of the cameras need to be determined (Figure 2.2) (Park, Koch, & Brilakis, 2011).

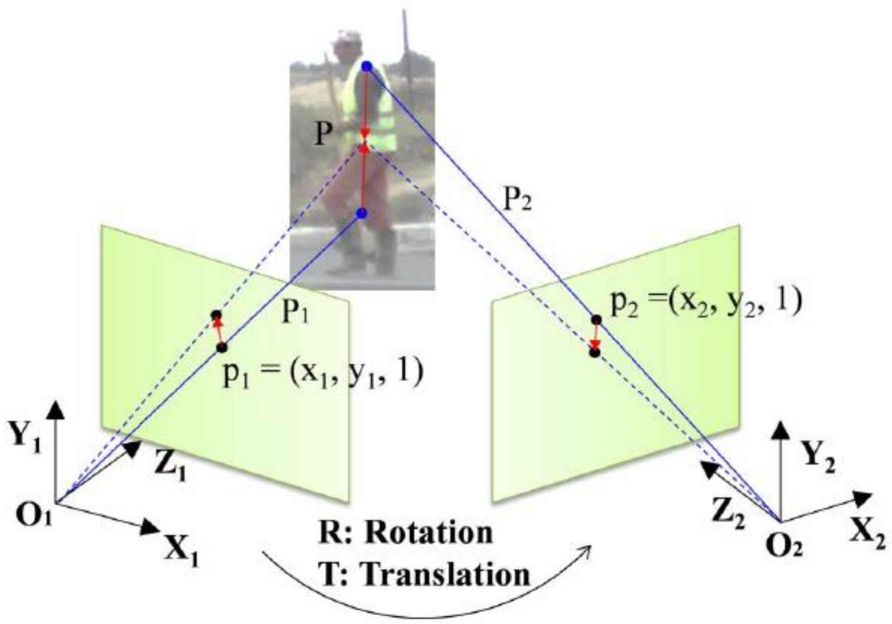


Figure 2.2 Epipolar geometry and triangulation example illustrated by Park et al. (2011).

Epipolar geometry describes the relationship between the positions of corresponding points in a pair of images (Svoboda & Pajdla, 2002; Zhang, 1998). It can be established from a few image correspondences and is used to: (i) correspond the position of points; (ii) compute the displacement between the cameras and (iii) reconstruct a 3D object-space (Svoboda & Pajdla, 2002). Triangulation refers to finding the intersection point of two or more centroid coordinates (Park et al., 2011). In photogrammetry, camera triangulation refers to the reconstruction from two or more images' pixel coordinates (Hartley & Sturm, 1997). The intersection of the light rays may be skewed due to lens distortions caused by light refractions, disparities in camera field of views and/or human errors from the manual digitisation process (see Figure 2.2) (Park et al., 2011). To enhance the accuracy of triangulation, Hartley and Sturm (1997) proposed a method to correct centroid relocation (Figure 2.3). The optimal coordinate vector was found by increasing the number of cameras viewing the same corresponding point (Bouguet, 1999). Based on these insights, the study design for the 3D kinematic analysis in this thesis ensured four SwimPro cameras viewed the same corresponding control point or anatomical landmark when capturing the freestyle and drill swimming movement.

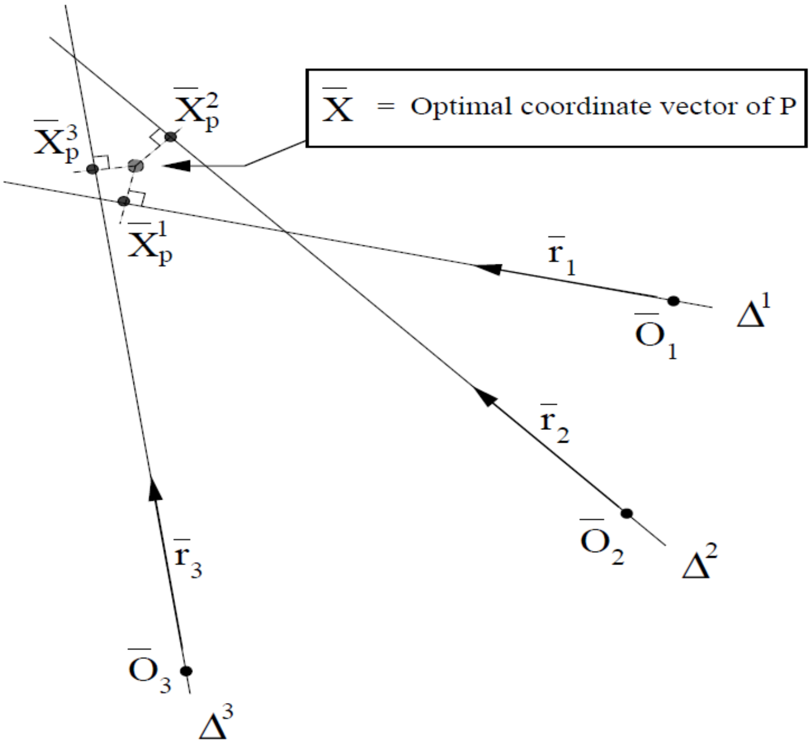


Figure 2.3 Enhancing 3D triangulation from multiple camera views (Δ^1, $\Delta^2$and Δ^3) illustrated by Bouguet (1999).

2.4.5.1.2 Camera calibration

The calibration of a video image for 2D quantitative analysis requires a scaling or reference object, whose dimensions are accurately known, to be captured in the plane of view (Mooney, Corley, Godfrey, Os-borough, et al., 2015). This enables the 2D video pixel coordinates to be transformed to object-space or real world coordinates during the digitisation process (Mooney, Corley, Godfrey, Os-borough, et al., 2015; Payton, 2008). When looking at 3D analysis, a different calibration technique is advised. This is referred to as photogrammetric calibration (Fraser, 2001; Zhang, 2000). Equations 2.2 and 2.3 can be combined together into different workable forms; see Equations 2.4 and 2.5 (Kwon & Casebolt, 2006). Equation 2.4 is used for the camera calibration whereas Equation 2.5 is used for the 3D reconstruction (Kwon & Casebolt, 2006).

$$\begin{bmatrix} x & y & z & 1 & 0 & 0 & 0 & 0 & -ux & -uy & -uz \\ 0 & 0 & 0 & 0 & x & y & z & 1 & -vx & -vy & -vz \end{bmatrix} \begin{bmatrix} L_1 \\ \vdots \\ L_{11} \end{bmatrix} = \begin{bmatrix} u \\ v \end{bmatrix} \quad [2.4]$$

$$\begin{bmatrix} L_1 - uL_9 & L_2 - uL_{10} & L_3 - uL_{11} \\ L_5 - vL_9 & L_6 - vL_{10} & L_7 - vL_{11} \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} u - L_4 \\ v - L_8 \end{bmatrix} \quad [2.5]$$

Photogrammetric calibration involves the process of numerically finding the DLT coefficients of each camera (Kwon & Casebolt, 2006). This calibration is based on a set of six or more control points, typically fixed to a static calibration frame. The control points create a control volume whereby the Cartesian coordinates of the 3D object-space are known (Dadashi et al., 2013; Figueiredo, Machado, Fernandes, & Vilas-Boas, 2011; Kwon & Casebolt, 2006; Payton, 2008; Zhang, 2000). Literature has demonstrated that the number and distribution of control points on the calibration volume, either above- or below-water, affects the 3D reconstruction accuracy (Brandão, Figueiredo, Gonçalves, Vilas-Boas, & Fernandes, 2010; Chen, Armstrong, & Raftopoulos, 1994; de Jesus et al., 2015; Figueiredo, Machado, et al., 2011; Gourgoulis, Aggeloussis, Kasimatis, et al., 2008; Psycharakis et al., 2005). Brandão et al. (2010), reported that for a calibration volume of 3 x 3 x 3 m in size, which was recorded simulatively by four under- and two above-water cameras, a set of 20 underwater and 16 above-water control points produced the most accurate 3D reconstruction. For freestyle stroke analysis, a larger rectangular calibration volume (6 x 2.5 x 2 m) is recommended, as it allows for at least one stroke cycle to be captured (de Jesus et al., 2015). To ensure accurate 3D reconstruction, it is recommended that, as the calibration volume increases, the number of control points also increases (Chen et al., 1994; de Jesus et al., 2015; Psycharakis et al., 2005). A calibration frame and number of control points reported by de Jesus et al. (2015) will be used for the 3D kinematic studies within this thesis.

The 2D pixel coordinates of the control points are directly obtained from manual or automated digitisation. Equation 2.4 can be expanded to accommodate for the number of control points, although the number of equations must be greater than the number of unknowns (Kwon & Casebolt, 2006). Using the least mean square or singular value decomposition approach, the DLT algorithm calculates the DLT parameters (Kwon & Casebolt, 2006). The least mean square approach is also known as the standard DLT approach, whereas the singular value decomposition approach refers to a modified DLT approach. As previously stated, the DLT algorithm assumes a collinearity condition, which is not present underwater. Therefore, the methodology for the 3D kinematic analysis in this thesis will ensure that the lens distortions is corrected before the control points and anatomical landmarks are digitised.

The reconstruction process involves calculating the 3D object-space coordinates (x, y, z) of a given point based on the photogrammetric calibration data (Kwon & Casebolt, 2006). The accuracy of the reconstructed 3D object-space coordinates can be determined by the Root Mean Square (RMS) reconstruction error (ε_{RMS}) or the maximum reconstruction error (ε_{max}); see Equation 2.6 and 2.7 (Kwon & Casebolt, 2006).

$$\varepsilon_{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} {\varepsilon_i}^2} \qquad \textbf{[2.6]}$$

$$\varepsilon_{max} = \max\left(\varepsilon_1, \ldots, \varepsilon_n\right) \qquad \textbf{[2.7]}$$

The size of the calibration volume and DLT approach undertaken influences the reconstruction error. The RMS error tends be greater the larger the calibration volume (Gourgoulis, Aggeloussis, Kasimatis, et al., 2008; Kwon, Ables, & Pope, 2002). For a rectangular calibration volume 4.5 x 1.5 x 1.0 m in size, Psycharakis et al. (2005) reported RMS error values of 3.9, 3.8 and 4.8 mm for the x, y and z axes respectively. This error represented 0.1%, 0.2% and 0.5% of the rectangular calibration volume. For a larger calibration volume, de Jesus et al. (2015) reported RMS reconstruction errors ranging from 4.06 to 6.16 mm for the above-water cameras and 4.04 to 7.38 mm for the underwater cameras, which are also considered acceptable errors for swimming movement analysis.

A modified DLT approach, called the DLT double-plane (DLT DP) method, involves two parallel control planes rather than a whole calibration frame structure (Drenk, Hildebrand, Kindler, & Kliche, 1999; Elipot et al., 2009). When all control points and movement are within the calibrated volume, the DLT DP method has been shown to reduce reconstruction error as no extrapolation is required (Elipot et al., 2009; Kwon et al., 2002). However, when movement is outside the calibrated volume and extrapolations may be required, visual calibration may offer a more improved reconstruction accuracy compared to the photogrammetric calibration method (Elipot et al., 2009). The visual calibration method calculates the internal and external parameters of the camera directly and aims to solve the following equation (Equation 2.8) (Elipot et al., 2009):

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} \sim \begin{bmatrix} f_u & \alpha & U_0 \\ 0 & f_v & V_0 \\ 0 & 0 & 1 \end{bmatrix} \cdot R \cdot \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} + T \qquad [\mathbf{2.8}]$$

Where $\sim$ is the non-zero scale factor; $u, v, 1$ are the image plane coordinate vectors (pixels) of a point, P; f_u, f_v are the focal length (pixels); α is the skew coefficient defining the angle between the pixel axes; U_0, V_0 are the principle point coordinates; R is a 3 x 3 rotation matrix; $X, Y, Z, 1$ are the space coordinate vector of same point, P; and T is a 3 x 1 translation matrix (Elipot et al., 2009).

Similar to the photogrammetric calibration, the visual calibration method determines the internal parameters of each camera ($\mathrm{f_u}$, $\mathrm{f_v}$, $\mathrm{U_0}$, $\mathrm{V_0}$ and α) (Elipot et al., 2009). These internal camera parameters are inferred from images from the planar chequered board grid. The external parameters of each camera (R and T) are inferred from an image of the control points on the calibration volume. Elipot et al. (2009) illustrated that both visual calibration DP and DLT DP methods provide an improvement to 3D reconstruction accuracy. Therefore, the camera setup and movement parameters under investigation will determine which calibration method is employed in this thesis.

2.4.5.2 Individual-based analysis

Individual-based analysis, or single subject design, is the evaluation of a problem within a single-subject and is important for the accurate biomechanical assessment of a skill movement (Ball & Best, 2012; Ball et al., 2003a; Bates, James, & Dufek, 2004; Dufek, Bates, Stergiou, & James, 1995). Individual-based analysis can also provide important information that might be masked in a group-based analysis approach (Ball & Best, 2012; Ball et al., 2003a; Barris et al., 2014; Bates et al., 2004; Dufek et al., 1995). For example, looking at weight transfer in the golf swing, Ball and Best (2012) reported individual-specific relationships in centre of pressure parameters and club head velocity. Notably, golfers returned different combinations of significant factors that were not evident in the group-based analysis (Ball & Best, 2007). As these factors would not have been identified using only group-based analysis, the possibility to offer technique recommendations specific to the individual would have been hindered (Ball & Best, 2012).

Individual-based analysis can also avoid statistical errors that are produced when participants use adaptive movement behaviours to perform a specific skill or training task (Bates et al., 2004). That is, when individuals adopt varying movement responses to achieve a particular performance outcome, inter-subject variability increases. Consequently, the statistical power of the group-based analysis will reduce which can result in a false support of a null hypothesis depending on the distribution of subjects (Bates et al., 2004; Button, Davids, & Schollhorn, 2006; Caster & Bates, 1995).

While group-based analyses have provided important information relating to the biomechanical effects practice tasks can have on performing the full skill (Brackley, Tor, et al., 2020; Reid et al., 2015; Reid et al., 2010), important individual-specific findings have been reported between and within individuals (Barris, Farrow, et al., 2013; Barris et al., 2014). Further, individual-based analysis has proven particularly useful in understanding performance data of elite athletes (Button et al., 2006; Kinugasa, 2013). In elite Australian diving, Barris, Farrow, et al. (2013) examined differences between completed dives and those of baulked take-offs on an individual basis (n = 6). While there were no observable differences between performance conditions for all participants, individual differences were observed in the hurdle and approach phases (Barris, Farrow, et al., 2013). The authors suggested that the individualised analysis undertaken provided unique insights into how elite individuals perform and adjust movement responses (Barris, Farrow, et al., 2013; Barris et al., 2014). From a dynamical systems theory perspective, individual-based analysis of kinematics is also preferred in order to unravel the complex processes governing motor control (Button et al., 2006). Consequently, individual-based analysis provides a clearer picture of how performers exploit variability and is considered most appropriate for the individual in terms of skill development (Ball et al., 2003a; Button et al., 2006).

There is further evidence of individual-specific findings in the elite sport setting in rifle shooting (Ball et al., 2003a), air pistol shooting (Ball et al., 2003b) and swimming (Tor, Pease, Maloney, Ball, & Farrow, 2018). In rifle shooting, Ball et al. (2003a) examined body sway, aim point fluctuation and performance from a group- and individual-based analysis approach. Six elite shooters performed 20 shots at a target under competition conditions. While there were no significant relationships between body sway and performance from a group-based analysis approach, all shooters returned significant correlations and regressions when the relationships were examined from an individual-based analysis approach (Ball et al., 2003a). Further, the authors identified important technical information in the group-based analysis that was not evident in the individual-based analysis. It was concluded that individual-based analysis is most appropriate in terms of providing specific technique recommendations for the individual and therefore, should be included within group-based analysis in order to extract all the available information (Ball et al., 2003a). Additionally, Tor et al. (2018) investigated the underwater trajectory of the swimming start using an individual-based analysis approach to illustrate the non-linear and individualised learning responses of three elite swimmers. These studies support the suggestion that training programs should be individualised to the athlete's skill level in order to best facilitate skill learning and prepare the athlete for competition (Barris, Farrow, et al., 2013; Barris et al., 2014; Hodges et al., 2011; Saemi et al., 2012).

As previously discussed in section 2.3.2 (p. 25), decomposing the freestyle stroke into smaller components is a routinely prescribed practice approach in swimming (Junggren et al., 2018). Such practice tasks are believed to help 'perfect' swimming technique, which supposedly promotes greater swimming efficiency and mechanical consistency (Junggren et al., 2018; Lucero, 2015). However, the development of a ‘perfect’ swimming technique model is debated within the skill acquisition literature as variability in movement patterns within an individual can be viewed as a key facet to expert performance (Bartlett et al., 2007; Davids et al., 2003). Currently, there is no individual-based analysis on the kinematic comparison between freestyle and practice drills in swimming. The aforementioned studies provide strong support for including an individual-based analysis in the biomechanical assessment of sporting performance, especially at the elite level. Individual differences are expected given the swimmer’s own anthropometric, mechanical and physiological characteristics and their freestyle distance specialisation (Seifert, Button, et al., 2010; Seifert et al., 2013). Consequently, the confirmation of individual differences in freestyle and drill performance will directly affect how freestyle drills should be prescribed. Moreover, coaching recommendations may need to be tailored to the individual rather than developing a ‘perfect’ swimming technique model of ‘good’ technique. This thesis will use both a group- and individual-based analysis approach to provide a greater understanding of the effect of task decomposition drills on freestyle performance.

2.5 Summary

Swimming biomechanical research of the freestyle stroke has typically been concerned with understanding kinematic and kinetic features critical to performance (López et al., 2002; McCabe et al., 2011; Sanders et al., 2016). These research outputs have provided valuable contributions to our knowledge of the freestyle stroke. However, from an applied perspective, the learning processes and drill-based practice tasks prescribed in training have not been systematically examined to the same extent. The available evidence in swimming practice points to coaches prescribing practice drills that allow for the development of ‘perfect’ swimming technique where the aim is to promote greater swimming efficiency and mechanical consistency (Junggren et al., 2018; Lucero, 2015). However, such practice approaches can sometimes hinder positive skill and learning transfer as the movement responses may not be functional for, or representative of, performance in the competition environment (Barris et al., 2014; Davids et al., 2017; Pinder et al., 2015).

This review of literature introduces the RLD framework and its role in assessing and manipulating practice design. Several gaps in the literature have been identified, revealing the need to (i) explore the specific learning processes and practice tasks prescribed in the training environment of freestyle swimmers, (ii) biomechanically assess the action fidelity of commonly prescribed freestyle practice tasks from both a group- and individual-based analysis perspective and (iii) determine if transfer of skills and learning is positive or negative when athletes perform freestyle practice tasks. Therefore, this thesis will be the first to explore the most commonly prescribed freestyle drills prescribed by elite swimming coaches. Using this information, the effect drills have on the freestyle stroke will be assessed from a 3D biomechanics perspective, using underpinnings of RLD.

Chapter 3: Coaches' Perspective Towards Skill Acquisition in Swimming

"*If there is any one secret of success, it lies in the ability to get the other person's point of view and see things from that person's angle as well as from your own.*" – Henry Ford

This chapter is supported by the following peer-reviewed journal article:

Brackley, V., Barris, S., Tor, E. & Farrow, D. (2020). Coaches' perspective towards skill acquisition in swimming: What practice approaches are typically applied in training?, *Journal of Sports Sciences*. DOI: 10.1080/02640414.2020.1792703

3.1 Abstract

This study aimed to explore the experiential knowledge and preferred training approaches of elite swimming coaches. The practice approaches used for general skill development were investigated and then focused specifically on the freestyle stroke. A qualitative thematic analysis approach was employed to identify, analyse and report themes within the content of the collected data. Twenty elite swimming coaches participated in semi-structured interviews. Analysis revealed that the most common training practice employed to improve skill learning was task decomposition or part-task practice. Learning tasks were set within skill and speed progressions. The findings of these interviews highlight that the contemporary theoretical frameworks used to investigate the coupling between a performer and their environment are not fully understood or practically applied by swimming coaches. While swimming coaches seem to mix both traditional and contemporary skill acquisition theories in their training prescriptions, the traditional approach is dominant as evidenced by coaches still seeking to reinforce 'perfect' swimming technique and mechanical consistency. It is suggested that coaches' reluctance to apply more ecological approaches into their training programs could be due to their acclaimed successes using traditional training approaches and the lack of appropriate empirical findings applicable to the aquatic environment. Considering coaches' experiential knowledge and training prescriptions may benefit future research protocols and better facilitate the transfer of empirical findings to coaching practice.

3.2 Introduction

A considerable challenge for sport practitioners is ensuring that training practices facilitate the transfer of learning from training to competition (Maloney, Renshaw, Headrick, Martin, & Farrow, 2018). Whether intentionally or not, many still adhere to traditional theories of cognitive science and computation in skill practice approaches (Seifert et al., 2013). These approaches liken the mental processes of the human mind to a computer (e.g., capacity-limited device) heavily dependent on symbolic knowledge structures stored in memory to mediate consistent movement processes (Davids et al., 1994; Handford et al., 1997; Lavallee, Kremer, Moran, & Williams, 2012). According to this viewpoint, it is believed that the essence of skill acquisition is the ability to consistently and autonomously replicate a task movement that has been grooved to perfection in training (Davids et al., 1994; Seifert et al., 2013). For example, coaches may remove movement variability by decomposing a task into its component parts (e.g., the full swimming stroke is reduced into a kicking drill) (Davids et al., 2001; Ford et al., 2010; Reid et al., 2010) or progress a skill from basic coordination to the full movement, with an emphasis on volume and exact repetitions (Pinder et al., 2015). Such practice tasks are typically referred to as drills and prescribed within part-whole training approaches (Whelan, Kenny, & Harrison, 2016). They are designed to reduce performance complexities, develop skill automatization and help performers manage the attentional demands and information loads during skill acquisition (Davids et al., 2001; Ford et al., 2010; Reid et al., 2010). Yet, empirical evidence suggests that task decomposition may have a negative effect on the transfer of learning as it can alter movement behaviour in a manner atypical to competition performance (Barris, Davids, et al., 2013; Reid et al., 2010; Renshaw et al., 2007).

Historically, biomechanists and motor learning specialists have advocated practice tasks that promote the invariant repetition of a single ideal movement pattern (Brison & Alain, 1996; Davids et al., 2017; Schmidt & Lee, 2011). However, ecological dynamics approaches have argued variability in movement patterns can be viewed as functional when it supports the performance flexibility needed to adapt to changing constraints (Davids et al., 2008; Seifert & Davids, 2012). As this argument has garnered empirical support, there has been a shift towards encouraging coaches to identify and preserve the key constraints and information–movement couplings that athletes use to regulate behavioural patterns in specific performance contexts, in the design of their practice (Araújo et al., 2007; Krause et al., 2018; Pinder, Davids, et al., 2011b).

In this context, constraints are considered to be boundaries or features that limit (and enable) the dynamics of emergent functional behaviours (Newell, 1986). The constraints-led perspective classified constraints into three core categories: organismic, environmental and task (Newell, 1986). Further, the constraints-led perspective highlighted how, through the dynamic interaction of constraints during goal-directed activities, a learner will self-organise in an attempt to generate functional movement solutions (Renshaw et al., 2010; Renshaw et al., 2019). For example, in manipulating the task constraint of swimming speed and the environmental constraint of fluid flow in a flume, Guignard et al. (2019) illustrated how elite swimmers are able to maintain performance by adapting their arm-to-leg coordination patterns.

Early motor learning research contend that learning is specific to the visual information sources present during learning and that skill performance deteriorates if there are changes to the information present in a transfer test (Proteau, 1992). Largely derived from a simple research design, the specificity of learning hypothesis (Proteau, 1992) has been generalised to more applied sport skill training contexts by referring to the extent to which the training reflects the conditions typically experienced during competition performance (Farrow & Robertson, 2017). More recently, ecological dynamics research investigations have advocated representative learning design (RLD), in place of specificity, which argues that learning is specific to the interaction of all the constraints (not just visual information) during practice.

The RLD concept has been proposed as a framework for coaches to enhance the skill learning of their athletes and for researchers and sport scientists to assess the extent to which the practice and experimental tasks they design are representative of the information (e.g., perceptual stimuli, task constraints) encountered in the performance context (Krause, Farrow, Buszard, et al., 2019; Pinder, Davids, et al., 2011a, 2011b). Functionality and action fidelity are two key principles within the RLD framework that guide the assessment of practice tasks (Pinder, Davids, et al., 2011b; Pinder et al., 2013). Understanding both the functionality and action fidelity of the practice design ensures that the complexities of performance and the coupling between key intention, perceptual and action processes are maintained (Pinder et al., 2013). Functionality refers to the degree to which a performer can regulate their decisions and movement solutions in the learning context with comparable information sources present during performance environment (Davids et al., 2013; Pinder, Davids, et al., 2011b). For example, the use of a swimming flume to artificially amplify drag (Guignard, Rouard, Chollet, Hart, et al., 2017) is likely to reduce the functionality of the task as information-movement couplings relating to the competition environment are removed (Krause et al., 2018). The concept of action fidelity refers to the correspondence between movement behaviours in a reference situation such as the performance environment and movement behaviours in the experimental or simulated situation such as the training environment (Araújo et al., 2007; Pinder et al., 2013; Stoffregen et al., 2003). In swimming, decomposing the full freestyle stroke into a single arm drill to infer transfer benefits can be viewed as an example of low action fidelity as empirical findings have illustrated that single-arm freestyle reduces hip velocity and causes different body rotation patterns compared to the movement kinematics of competition (Arellano et al., 2010). In this respect, the RLD challenges traditional practice approaches that decompose skills into smaller constituent parts as they may distort or decontextualize the integrated relations between sub systems and hinder skill learning (Barris, Farrow, et al., 2013; Pinder, Davids, et al., 2011b; Seifert et al., 2013). While there has been a significant amount of research investigating RLD within sports coaching settings over the last decade (Barris, Davids, et al., 2013; Guignard, Rouard, Chollet, Hart, et al., 2017; Pinder, Davids, et al., 2011a), it remains unclear how well the concepts have been incorporated by coaches in practice.

To gain a better understanding of the extent skill acquisition principles have been translated into practice, researchers have explored the experiential knowledge and practice prescriptions of elite coaches (Greenwood et al., 2012, 2014). Interview data from elite coaches from track and field, gymnastics and cricket revealed that the coaches' experience-based intuitions often complemented the empirical research (Greenwood et al., 2012, 2014). Coaches expressed ideas consistent with recent knowledge of perception-action coupling and constraints-led approach in the design of training programs. Observations of elite swimming training have revealed that coaches emphasise principles of deliberate practice within their training programs where they strive for repeatable execution of technique (Junggren et al., 2018). The priority coaches places on these practices is indicative of the importance they place on time spent in specific technical practice from an early age (Côté & Gilbert, 2009; Ericsson et al., 1993; Junggren et al., 2018). In contrast, experiential data drawn from elite coaches in rugby league (Rothwell et al., 2017) and field hockey (Slade et al., 2015) provide support for representative game scenarios where players draw on other sports experiences and learn to regulate and adapt their performance actions (Araújo & Davids, 2015). While both practice approaches seek to train the athletes in a manner that ensures transfer of learning to competition, a fundamental philosophical difference exists centred on the relative importance the coach places on how the athletes execute their skills. Swimming coaches strive for execution of the same action repeatedly, whereas the rugby and hockey coaches encouraged their athletes to develop adaptable movement patterns.

Coaching research in swimming has typically been concerned with understanding performance improvement from a physiological or biomechanical perspective (McGowan, Pyne, Raglin, Thompson, & Rattray, 2016; Mooney et al., 2016; Nugent, Comyns, & Warrington, 2017). In contrast, the learning processes underpinning enhanced performance has not been systematically examined to the same extent. Inspection of high-performance training practices may identify that coaches possess understanding of many skill acquisition principles despite not necessarily being aware of key theoretical ideas (Greenwood et al., 2012). Accordingly, the aim of this study was to identify the most common training practices used by elite swimming coaches, specific to skill development and freestyle. A specific focus was placed on freestyle as freestyle training prescriptions dominate most of the season regardless of swimmers' specialisation in one of the other form strokes (Counsilman & Counsilman, 1994; Deschodt et al., 1999; Stewart & Hopkins, 2000; Yanai, 2003). The research questions guiding this study were: What skill acquisition approaches do swimming coaches apply in training? What are the key goals behind the freestyle training tasks (drills) most commonly prescribed by swimming coaches? Based on the applied insights of the authors and previous coaching observation research (Junggren et al., 2018; Slade et al., 2015), it was anticipated that elite swimming coaches heavily apply traditional motor learning approaches including part-task training through the prescription of drills in their practice prescription; yet have an understanding of more contemporary skill acquisition approaches. Integrating the experiential knowledge of expert coaches with empirical data has proven to provide valuable foundational support for practical applications in learning design (Davids et al., 2017; Greenwood et al., 2014).

3.3 Methods

3.3.1 Philosophical assumptions

This study is situated within an interpretive paradigm and framed by ontological relativism and epistemological constructionism (Braun & Clarke, 2013; Smith & Sparkes, 2013).

3.3.2 Participants

Twenty elite Australian swimming coaches (19 male and 1 female) voluntarily participated in the study. The recruitment of these participants was informed by purposeful (criterion-based) sampling to ensure key informants in the field of high-performance swimming could address the topic of investigation the most productively (Fleming, Young, Dixon, & Carré, 2010; Patton, 1999, 2002; Thompson, Bezodis, & Jones, 2009). To be eligible, participants had to: (a) have experience working in high-performance swimming with freestylers and (b) be willing to openly share thoughts and practice examples regarding skill acquisition. Among the 20 participants, six were classified 'Platinum' level coaches by the Australian Swimming Coaches and Teachers Association (ASCTA) which is the highest recognition of achievement given at the elite level. These coaches, aged between 49 and 70 years (M_{age}=60.64 years, SD = 8.34), had a minimum of 20 years coaching experience ($M_{experience}$=34.83 years, SD = 11.20) and/or were on the Australian national coaching team. The remaining 14 participants held either a 'Gold' or 'Silver' high-performance qualification given by the ASCTA which is the second and third highest recognition of achievement at the elite level, respectively. These coaches had between 8 and 39 years of coaching experience ($M_{experience}$= 22 years, SD = 10.38) and were aged between 28 and 61 years (M_{age}= 44.49 years, SD = 10.38) at the time of the interview.

Ethical approval to conduct the study was sought and provided by the Victoria University Human Research Ethics Committee (see Appendix A – Participant information and consent). Members of the research team approached and recruited the participants, either in person or via email, informing them of the nature of the study. Participants agreed upon convenient times for the interviews and gave informed consent before data collection.

3.3.3 Data collection

To address the research aim, face-to-face semi-structured interviews were conducted by the first author who was trained in qualitative research and engaged with elite swimming coaches and athletes on a regular basis. The interview guide was divided into three main sections starting with warm-up questions on the coaches' swimming background and experiences. The second part of the interview guide focused on coaches' approach towards skill and technique development using questions such as "How do you teach skill and technique development within your squad?". This was followed by questions looking specifically at the freestyle stroke and drill prescription (e.g., "What types of drills do you find most effective when you are working on developing skill and technique in your squad?"). Probes were used throughout to engage further elaboration or to ensure the participant's description was accurately understood (Louise & While, 1994; Patton, 2002). This approach ensured that the responses given were consistent in terms of depth and complexity yet allowed the flexibility to pursue responses beyond the scope of the specific interview questions (A. Fontana & Frey, 2005; Hardy et al., 2017). Furthermore, the semi-structured approach was adapted to reflect the nature of such interviews where participants will often cover tangent points of interest or make observations not necessarily anticipated by the interviewer (Slade et al., 2015).

The interview guide was developed by all four authors and was reviewed by an independent expert in the field of qualitative research (Hardy et al., 2017). The independent expert had a PhD in psychology, over 10 years' experience working in health psychology and conducted multiple research outputs in social science, epidemiology and public health disciplines. Pilot interviews were conducted with a non-elite coach and an elite coach (n=2) to assess the appropriateness of the topic areas and interview flow (Pilgrim, Robertson, & Kremer, 2016). This process ensured that the interviewer could understand the coaches' colloquial language and probe questions appropriately. As no adjustments were made to the interview guide, the interview results from the elite participant was included in the full analysis. All interviews were audio recorded, ranged between 23 and 48 minutes in duration ($M_{interview}$= 36.92 minutes, SD = 7.39) and transcribed verbatim by a professional transcriber. The NVivo 11 analysis software (QSR International Pty, Ltd, 2017) was used for the management and analysis of the interview data.

3.3.4 Data analysis

Inductive thematic analysis was used to analyse the interview data (Braun & Clarke, 2006; Braun, Clarke, & Terry, 2015; Braun, Clarke, & Weate, 2016). The six-stage thematic process began with (i) the researcher becoming familiar with the data through listening to the audio recordings, checking the transcription against the audio recording, reading and re-reading the final transcripts and making brief notes of prompted ideas relating to the research aims. The second stage (ii) consisted of organising data or identifying patterned responses into initial codes and then (iii) collating initial codes into potential themes and sub themes (constructing thematic map). The process of generating codes and potential themes was an active process where the first author drew from personal experiences and interpretation of the coach accounts (Braun et al., 2016; Patterson & Backhouse, 2018). At this stage, the findings were discussed in-depth with the principal supervisor. The researchers were mindful that given the ontological relativist perspective where realities are multiple and subjective, coaches' perceptions and training practices are likely to be diverse (Patterson & Backhouse, 2018). For this reason, the focus was on identifying patterns in the data that represent contrasting finding, not consensus. It is also worth noting that while the described process of thematic analysis appears relatively linear, the analysis undertaken was rather an interactive and cyclic process (Braun & Clarke, 2013; Braun et al., 2016). The fourth stage (iv) involved reviewing each interview transcript against the codes, themes and subthemes to ensure they fit within the overall research aim. During the fifth stage (v), the final refinements were made which included reviewing, defining and naming final themes. The sixth and final stage (vi) consisted of generating an accompanying narrative describing each theme in the context of the research question (Braun & Clarke, 2006; Braun et al., 2016; Pilgrim et al., 2016).

3.3.5 Research quality and rigor

Contemporary views to enhance the quality of this study included conversation with 'critical friends' and reflexivity (Braun & Clarke, 2013; Nowell, Norris, White, & Moules, 2017; Smith & McGannon, 2018). The research team acted as 'critical friends' who encouraged the first author to continually reflect on the interpretation of data and they also questioned the decisions made relating to the organisation and analysis of the data (Smith & Sparkes, 2013). Further, participants were sent their interview transcription and also offered to share any subsequent feedback (T. L. Williams, Smith, & Papathomas, 2018) . Two participants responded and reported that the data resonated with how they, as coaches, approach skill acquisition in their design and prescription of training tasks.

Throughout the study, the research team paid close attention to how their behaviours, thoughts and assumptions were impacting the research process (Braun & Clarke, 2013). The first author came from a non-swimming background, yet engaged regularly with swimming coaches during their regular training sessions. Additionally, the remaining members of the research team worked as a biomechanist or skill acquisition consultant in swimming and/or a broad selection of sports including cycling, tennis and Australian football. Reflexivity is crucial to qualitative research; therefore, given the interpretivist approach, the research team acknowledge their influence on the study design and processes. Further, the working relationship the participants had with some members of the research team may have shaped current practice approaches and responses given. To demonstrate rigor, the recruitment of participants continued until data saturation was achieved (O'reilly & Parker, 2013). Data saturation was claimed when no new codes or themes could be constructed from the last seven interviews as no new information was elicited (Fleming et al., 2010; Vella, Oades, & Crowe, 2011).

3.4 Results

The two high-order themes that were identified through thematic analysis included *Freestyle Drills* and *Acquisition of Technical Skills* (see Figure 3.1). The supporting subthemes are discussed and illustrated using representative quotes from the participant coaches (Nugent, Comyns, & Warrington, 2017). To secure confidentiality, participants were assigned a pseudonym label (e.g., SC1 - SC20).

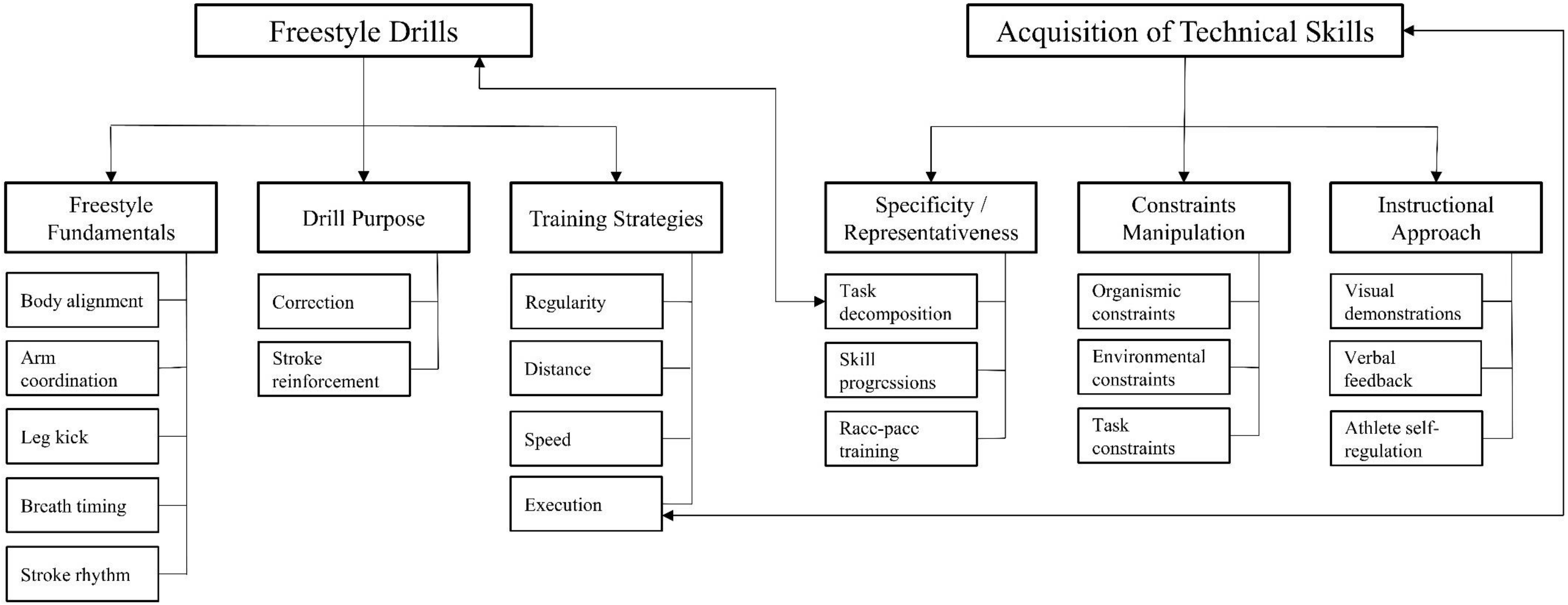


Figure 3.1 Australian swimming coaches' skill acquisition approaches in training and key goals behind the freestyle training drills most commonly prescribed.

3.4.1 Freestyle drills

All of the freestyle drills described by the participants involved breaking the stroke into component parts. In particular, sub-themes identified were categorized into *freestyle fundamentals*, *drill purpose* and *training strategies.*

3.4.1.1 Freestyle fundamentals

The freestyle drills mentioned by all participants were based around their outlook on the most important components (fundamentals) of freestyle. Most participants emphasized the importance of athletes' maintaining a good body alignment in the water and used words such as "posture", "body alignment" and "long axis" to describe the setup in the water. Other components such as the arms to create propulsion, the leg kicking action for balance, breath timing and stroke rhythm were acknowledged. Yet, the body position was illustrated as the foundation to swimming freestyle efficiently by sixteen of the participants:

> Body position and balance before everything…Everything else is ineffective without it. If you can't switch your core on, you can't apply force, you can't consistently kick well, you're compromising, you're in a high drag state and you're in a low propulsive state compromising both. There're only two things that are going to make you better in freestyle and that is decreasing your drag and increasing propulsion. If you're compromising both by those two things, you're stuffed. It starts at the central theme and everything else, pull weaknesses, kick weaknesses, are all derived from a lack of balance and a lack of body position. (SC2)

Over 20 freestyle drill variations were discussed, however only the drills mentioned by a minimum of six participants are presented. These drills, in order of most mentioned, include: (1) *single arm*, (2) *long dog*, (3) *polo*, (4) *kicking* and (5) *sculling*. A summary of the drills' description, key task goal and variations, as mentioned by the coaches, are presented in Table 3.1.

Table 3.1 Most mentioned freestyle drills, key task goals and variations.

Drill name(s)	Task goal(s)	Variations
Single-arm *"one arm freestyle"*	• Breath timing • Body position / alignment	Single arm swimming with non-swimming arm straight in front (slightly easier) or arm directly by the athlete's side.
Long Dog *"dog paddle"* *"short dog"*	• Catch position (hand entry) • Underwater recovery (pull phase) • Body rotation • Trunk alignment	
Polo *"head-up freestyle"*	• Catch position (hand entry) • Stroke rhythm (arm coordination) *"kayaking principle"*	*"head-up freestyle with butterfly kick"* or named *"Popov"*.
Kicking	• Body position / alignment	Kicking either placing arms straight in front (slightly easier) or arms directly by the athletes' side.
Sculling	• *"feel" for the water and to ensure that the "arms and body is in a position to perform well"*	

> The drills that I've used and probably continue to use, are things like that might isolate one part… So, body position, snorkel, with or without fins, hands by your side, just feeling the water getting the body position right so you're not under the water… long dog and then polo over the top working on entry point and finishing as well. And then some alternate swimming - six on left, six on right, six on whole preferably without breathing, and then adding the breathing in. So, it's sequential ensuring that each part, each important part which is body position, timing of the arms and legs, getting any rotation and making sure the patterning of the arms is right…So, I could have given you another different set of drills and progressions and there are many, many, many we haven't even touched on. But you have to keep coming back to what elements are important in freestyle and what is your swimmer's height, makeup, talent and capability. (SC10)

While fourteen of the participants mentioned various combinations and progressions of the single arm drills, one participant raised opposing comments:

> I do single arm drill but I'm just not convinced… It just seems awkward to me, always has done… I'm just not sure with the single arm whether in the long run it actually correlates… Timing and breathing, I think maybe that, but then it just always, it's not natural, you know… I just think the percentage of people doing it properly is very small. (SC3)

3.4.1.2 Drill purpose

All participants described that the purpose behind prescribing drills was to either (i) "fix" or (ii) "reinforce/activate" technique. Two coaches noted that for senior athletes, drills are predominately prescribed to "prepare for good technique" whereas for junior athletes, drills are used to fix technique flaws:

> I see drills for senior athletes as more of that [preparation for good technique], and I see drills for junior athletes as more of an exposure to an area of the stroke you see is flawed…. so you isolate it [the particular skill], put it under pressure, correct it and then try to condition it. (SC16)

When describing the use of drills to address a weakness in the swimming stroke or reinforce aspects of technique, seven of the participants cautioned on potential negative consequences associated with over- or misuse:

> I would say, and this is the problem with any drills that if you're using it to focus on a specific aspect, nine times out of ten it's going to negatively affect at least one other part of the stroke. So, whenever you use a drill you've got to understand is, I know at one stage it was all the rage especially when I was swimming catch up freestyle… so you've got to be very mindful of the affect. (SC4)

> You're not trying to swim in the drill, you're trying to use the drill to address an aspect of the swimming that will improve with the whole stroke of swimming – not have you swim like the drill. (SC11)

3.4.1.3 Training strategies

Participants described the swimming regularity, distance, speed and execution of the drills within their weekly training program. When asked where in the session drills are prescribed, all described that drills are often placed in the warm-up (prior to the main set) as athletes "have greater attention." Nonetheless, placing drills in the recovery (post main set under fatigue) or in the main set, with the intended goal of applying pressure or load to some of the drills, were other perspectives mentioned by eight of the participants.

> I think I did them probably both in the beginning as part of a warmup, but also would use them as a bit of a recovery as well at the back end of the session. And have used them even in a main set where there has been, trying to apply even a load to some of the drills as well. So just depending on a particular time of the season or really what I was looking for. And sometimes even just be doing drills if, as an aid to recovery as well, just low level aerobic (SC17)

Conversely, one participant raised concerns in regards to the whole approach to skill learning and development in swimming. This participant explained that in the warm-up coaches are often distracted by tasks such as writing the session on their whiteboard when they should be continually watching their athletes to ensure technique is maintained:

> You tell me a program you've been to and they [the athletes] haven't just flopped up and down in the warm up and the coach hasn't been on the side watching what they're doing… So, if a coach comes in and writes a session on the board and then carries on writing once the swimmers have got in [the water], he isn't going to be looking at the skill acquisition. So, to say they do the drills and all that in the warm up, it doesn't mean a lot. (SC3)

As drills are often placed in the warm-up, one participant illustrated how drills are incorporated within the prescribed 2 km warm-up, for example. The specific distance of drill swimming varied among the participants from 200 m to 800 m. Ten of the participants explained how they only prescribed 25 m or 50 m of drill at a time before incorporating freestyle swimming again:

> I think it's pointless in my view giving someone 400 m of drills. Because drills are very difficult to do, they're very hard to do. Concentration's got to be 100%. So, my rules are … this is just for me, I'm not saying it's right or wrong. We stick normally to 25 meters. Because over 25 meters they're able to hold and focus and concentrate more I believe than giving a 50 [of] drill. Having said that I do do 50's but I do more 25's than I do 50's. Especially for freestyle…. So, the warmup might be two kilometres and there might be 400 m, or 300 m, or 200 m of drill work in there. Most sessions I do it. (SC12)

When participants were asked what speed drills are performed at, there were mixed responses. Notably, six of the participants explained that the speed at which a drill is swum depends on athlete skill level, if the drill is reinforcing or correcting technique and the training variation, as stated by these participants:

> I think it depends on the level of the athlete and the level of the skill. So, say if you're working on your kick timing so your timing of your up kick would be catch position, that's, you have to start slow and then get close. If you're looking to reinforce it because they know how to do it or you can do, it's closer to race specific speeds. (SC1)

> I'll do single arm with a slow speed and I'll do single arm with a fast speed as well. So, for example you might go 25 metres left arm, both arms out in front, left arm, then I'll go 25 swim to the end, then I'll come back right arm slow, might do four, five, six times. Then I'll do it fast, where they're trying to work at hand acceleration, where it's similar to what they're doing with their stroke. (SC12)

Throughout the participant's illustration of the drills, seventeen participants made mention of using drills within a progression – starting with a simpler drill and building the complexity with the inclusion of full freestyle swimming or starting at a slower pace and increasing speed, as several participants explained:

> I didn't have one drill but basically hundreds of combinations to train different skills. And every time challenge them a little bit different and always followed by just proper swimming on various speeds, maintaining their skill. And if I could see they can't do it, go back to the drill and try it again. So really deconstruct the stroke a little bit and try to build it and progress it from skill level. (SC9)

> A series of drills might need to be linked, like I've just talked about, to get to the outcome in the swimming that you're after. Often, we just don't use a drill in isolation. There's usually a progression then to swim. Then we could continue to swim to consolidate. There's no value in doing some drills, say, in freestyle, and not swimming in the end. (SC11)

Two of the participants also expressed differing training prescriptions of drills implemented within their program:

> I got them to make them to make up their own drills and then try and teach that to someone else. And a big part of it the program is I always put in an element of play… Kids these days they don't have that natural feel for the water or that athletic intelligence on stuff… The way you discover is by playing, so just go and do what you want, swim backwards, do whatever. So, we do that and some of kids think it's a waste of time while others are, ah geez, I felt this. (SC5)

> I don't do as many drills as a lot of people. It's more attentional focus swimming… It's more what your focus is on or what you're trying to achieve. (SC1))

Further, one of the participants expressed how his session planning and coaching approaches has changed since his involvement with a skill acquisition consultant:

> I think my coaching's changed, he [skill acquisition consultant] helped me actually just believe in myself a little bit more. There're some things that I play around with my coaching and having a stamp of approval from him in making me believe that that's the way forward… I think we [as coaches] get caught up in doing the volume day after day and we don't look at the detail of it. [For example, adding a fatigue component when periodising a skill change]. So, I try to be a little bit smarter with my planning. (SC5)

Acquisition of technical skills

The participants' outlook towards skill learning and transfer was described in this high-order theme. Training practices mentioned to improve technical skills were categorised into three subthemes: *specificity/representativeness*, *constraints manipulation* and *instructional approach*.

3.4.1.4 Specificity/representativeness

Ten of the participants acknowledged that behaviours in training should be representative of competitive performance, as this participant stated:

> I think it's very important to swim freestyle at training how you want to race freestyle. So, what you do at training can't be a different looking stroke, and a lot of swimmers make that mistake…. (SC19)

The training practices mentioned included task decomposition, task progression and race-pace (speed) training. All participants illustrated that they "break the stroke down" or isolate particular segments, in order to simplify and facilitate skill learning, before reintegrating the segments back into the full stroke:

> Generally, there's too many things for them to work on. So, we break it down and put it pretty simply to see if we can create the change. By slowly bringing back some of the complexities to the stroke and then adding speed and pressure, they're more likely to get change. (SC14)

Fourteen participants also referred back to the same principles of skill progression they described in regards to the execution of freestyle drills to ensure transfer was achieved when swimming the full stroke:

> So, for example you might go 25 meters left arm, both arms out in front, left arm, then I'll go 25 swim to the end, then I'll come back right arm slow, might do four, five, six times. Then I'll do it fast, where they're trying to work at hand acceleration, where it's similar to what they're doing with their stroke. So, I get them doing it at slow speed and I'll just get them feeling. (SC12)

Ensuring the development of swimming speed for competition was noted by six of participants:

> Well race-pace is super important to me because it's really all that we're preparing for. Everything… Like I'll do this, there's plenty of other aspects of the program but they're all built in towards if I can do pace well. I mean a race is pace, that's just practice pace work and for me there is sometimes a gap between training and racing that the kids don't know how to execute so everything is built around pace and I'm after getting their pace right and they're improving and they're doing it well and they're technically good with it and they're specific to what they want to do in a race and we build the program around that and they've got the best chance of swimming faster. (SC2)

3.4.1.5 Constraints manipulation

Twelve of the participants explained how the personal characteristics of an individual (e.g., organismic constraints) can affect the acquisition of technical skills:

> There's a general plan for the whole group and then you've got to individualise it from there because everybody's going to respond differently. (SC4)

> You're looking at each individual athlete because each of those athletes will respond differently to certain sorts of stimuli. So, I'd have two sprinters at the same time and same age, but you'd have to train them differently. (SC20)

Further, eight of the participants illustrated that they make modifications to practice tasks and environments in the attempt to promote adaptive behaviours required in competition performance:

> I think when I watch in the training environment people are able to perform and make great decisions, but can they do it under the constraint of competition?… I want to train my athletes' capacity to think under all the constraint they're going to have at an event whether its pressure, lack of oxygen, lactate or fatigue - lots of different things. I try and simulate all of those stresses in the training environment, all of those stimuli, for not only a physiological response but also then from a skill acq perspective. Can they perform the task under any different constraint that I give them? I want them to be able to execute a great decision under the worst circumstances… I'm going to preload them with one goggle blindfolded. I'm going to preload them with lots of different sounds... So, a bit of interference. So, lots of different things to train the brain's ability to have a greater capacity for making good decisions under pressure. (SC6)

> I do a lot of sensory swimming. Like swimming with a sponge on or with a static rope or with something like paddles… [I think] good timing and body position is important in freestyle swimming but some drills [decomposed tasks] throw your timing out. This is why I rather do a lot of sensory swimming. (SC18)

> So, I would say that a lot of the time we do a body position drill is more to increase the awareness of where the body is in space, even though they're trying to improve it by decreasing… So, we might put weights on them or the opposite and make them more buoyant by putting like a buoyant strap under their hips and stuff. So, it's just a contrast. But does that position of hands by side kick exactly the same as when they're swimming? No. But does it improve one or the other by increasing awareness I say, yes. (SC1)

3.4.1.6 Instructional approach

The instruction process used by the participant coaches to help their athletes learn and acquire technical skills included: visual demonstrations, providing feedback and athlete self-regulation of performance. All participants indicated how verbal instructions are often used with visual demonstrations to both convey information and provide feedback and cues to the athlete in regards to technique:

> I'd always provide feedback if I could visually, iPad, iPhone, whatever, just so you could see that you need the change. And then what I'd do is, I'd say – I try to stay away from the word "feel"– but I'd say, are you noticing a difference in position? What do you notice? And I'd listen for you to say cues to me that I could use back to you. (SC16)

> If they [the swimmers] hadn't seen the drill I'd say, okay, you do this drill, this is the drill, one of my guys who's used to the drill, you demonstrate, so they [the swimmers] watch it, they see it, okay, they understand. So, it's how you explain it and I think you have to let them see it as well as explaining it. So, there's an old saying an eyeful is better than a gob-full and it's very true. (SC19)

One participant also explained the importance of providing constant feedback and correction to the athlete when working on addressing a weakness in the swimming stroke or reinforcing aspects of technique:

> So, I think when they're doing the drills you talk to them and I think you've got to be there and you've got to be correcting. If they're doing you know 16 25's of drill/swim or whatever, you can't make a comment about technique on number 15. I think you need to be there making it sort of all the way along, watching them when they're doing their drill, not just allowing them to do a drill on their own. (SC12)

Thirteen of the participants acknowledged that the coach can provide the training plan and practices but, ultimately, the athlete needs to take ownership of their own program. Consequently, athletes are encouraged to ask questions, do their own research on successful swimmers and self-regulate their performance:

> And all my coaching's based around reward and consequence. As a coach I'm not the reason they swim. They're the reason they swim. They're the reason they get the performance. So, in training I design it around them self-regulating their performance and self, they're driving the process so if they achieve what they need to achieve they're rewarded. If they don't achieve there has to be a consequence to that to make them shift their mind-set to be able to make the change. (SC5)

> I think the challenging part is rather than a coach just telling the athletes what to do, is to try and get them more empowered and asking them more questions and getting them more aware of what they're doing… So, trying to get them to be more engaged. (SC14)

> The swimmers who have the best technique think about it all the time. They're obsessed about it. (SC18)

3.5 Discussion

This study aimed to explore the variety of skill acquisition approaches applied by elite swimming coaches in their design and prescription of freestyle training tasks including how these approaches were applied to general skill development and learning. Using the six-step thematic analysis, two high order themes were identified: *Freestyle Drills* and *Acquisition of Technical Skills* (Figure 3.1). The schematic illustrates that while two distinct high order themes with supporting subthemes were constructed by the researchers' interpretation of the participant interviews, there are numerous overlapping findings between the two themes. Notably, the most mentioned freestyle drills illustrated by the coaches reflect the traditional motor learning practice of reducing movement variability by decomposing a movement task into smaller components (Davids et al., 2001; Ford et al., 2010; Reid et al., 2010).

3.5.1 Freestyle drills

3.5.1.1 Drill purpose

The purpose behind prescribing drills was twofold; (i) to improve aspects of the swimming technique by simplifying learning and (ii) to reinforce current technique performance. Two participants noted that in junior athletes the focus of drill prescription was on learning – implementing a set of underlying processes within practice to lead to permanent behaviour changes (Davids et al., 2008); whereas in senior athletes, the focus was to aid performance outcomes and technique. Recently, however, it has been shown that decomposing the full freestyle stroke into a single arm drill can cause significantly different hip and body rotation patterns than swimming the full freestyle stroke (Arellano et al., 2010).

Task decomposition in training practices may facilitate some skill learning; yet there is a debate within the skill acquisition literature whether the skills acquired during such practice approaches are transferable to the intended performance environment (Barris, Farrow, et al., 2013; Pinder, Davids, et al., 2011b; Seifert et al., 2013). The participants use of task decomposition practice approaches, contextualised within recent skill acquisition literature, highlights a possible disconnect between theory and practice. The results suggest that swimming skills are being overly deconstructed in the belief that working on isolated aspects of technique can then be transferred back into the whole skill, despite empirical evidence to the contrary.

3.5.1.2 Training strategies

Seventeen of the participants described prescribing drills at a slow pace and increasing the speed or progressing from a simpler to more difficult drill. While methods of task progression from basic coordination to competition-specific training are likely to provide a degree of learning success (Pinder et al., 2015), contemporary swimming research has demonstrated that the speed at which the full stroke (or drills) are swum can impact coordination patterns atypical to performance (Guignard, Rouard, Chollet, Hart, et al., 2017). Further, while participants typically located the drill practice at the beginning of the training session, eight of the participants also questioned whether this approach is transferable to competition racing especially when athletes fatigue (and technique "breaks down") towards the end of the race. These insights reflect that while swimming coaches are heavily biased towards traditional skill acquisition recommendations, many may be aware of and unknowingly apply contemporary skill acquisition principles.

3.5.2 Acquisition of technical skills

3.5.2.1 Specificity/representativeness and constraints manipulation

Participants indicated that a common training strategy believed to improve skill learning was to break the stroke into small constituent parts and/or using simplified stroke activities. Decomposing a learning task into manageable components is believed to help manage the information load on learning (Magill, 2007; Whelan et al., 2016). This was echoed among all the participants, despite applied research demonstrating that the transfer of learning may be limited by this approach (Davids et al., 2001; Reid et al., 2010; Renshaw et al., 2010). While removing movement variability and decomposing the freestyle stroke were common skill acquisition approaches, ten of the participants illustrated how they believe practice should be specific/representative to the intended performance outcomes. Such viewpoints may have been influenced by coaches' interaction with a skill acquisition consultant as one participant noted that through recent interactions with a skill acquisition consultant, he now incorporates fatigue components into his session planning when reinforcing or correcting skills.

Eight of the participants also illustrated the incorporation of contemporary skill acquisition approaches (e.g., constraints-led approach) into their training program when working on fundamental components of the stroke. For example, one of the participants described focusing on the complete stroke through the application of a sponge or hand paddles rather than prescribing drills that decomposed the skill. Schnitzler et al. (2011) found that adding a constraint (resistance provided by a parachute) to freestyle alters the propulsive phases and coordination parameters of the stroke; however, transfer of learning may be promoted as swimmers are encouraged to become more adaptive performers and attuned to their surrounding environment (Guignard, Rouard, Chollet, Hart, et al., 2017; Renshaw et al., 2009). Consistent with the rationale of Schnitzler et al.

(2011), one of the participants also agreed that some constraint manipulations (e.g., attaching weights to swimmer) may limit the swimmer’s ability to execute the skill ‘perfectly’; yet shared the belief that adaptable movement behaviours may be better promoted. Such insights demonstrate that some ecological theories are acknowledged and applied within the swimming training environment.

3.5.2.2 Instructional approach

In order to communicate technical information back to the athlete, participants stated that coaches must place their undivided attention on the individual. The instructional approaches used to facilitate skill learning involved using visual demonstrations and providing verbal feedback. Participants also highlighted the use of verbal cues to reinforce ‘perfect’ swimming technique and mechanical consistency when athletes perform specific technical practice tasks. Such training prescriptions may be the result of how many of the participants were coached themselves when they were swimmers, their coaching education, or the influencers from fellow coaches/mentors. Newell and Ranganathan (2010) has criticised, however, the use of instructions to impose an invariant movement pattern and rather argued that instructions should facilitate a learner’s search process towards effective coordination patterns.

3.6 Conclusion

This study provided insights into coaches' perspectives of skill acquisition in elite freestyle swimming. It is evident that swimming coaches view swimming as a complex motor skill that requires the invariant repetition of a movement pattern (Seifert et al., 2014). Thus, designing practice tasks to enhance skill learning is viewed as a balancing act between protecting the confidence of the athletes, by providing environments that enable them to be successful, versus exposing them to more demanding tasks or situations where they might be less successful (Renshaw et al., 2009).

The prescription of training practices that progress the swimming stroke from basic to full coordination, or decompose the stroke into component parts were common approaches used to develop skill among the swimming coaches sampled. Participants also indicated the use of constraint manipulations to better facilitate transfer of learning. The participant responses indicated that swimming coaches seem to intuitively use variants of the constraints-led approach in their practice design, yet they may be unaware of the theoretical context behind using it (Renshaw et al., 2019). The recent interactions some coaches had with a skill acquisition consultant may have begun to shape the implementation of such approaches in practice. Further empirical research is required to determine the positive or negative effect that the common training tasks have on skill learning, transfer and performance. Regardless, the experiential knowledge from coaches provides insights into swimming high-performance training programmes in Australia and can guide future research protocols to better facilitate the transfer of empirical findings to the performance environment (Greenwood et al., 2014).

3.7 Contribution of chapter to the aims of the thesis

The aim of Study One (Chapter 3) was to identify the most common training practices used by elite swimming coaches, specific to skill development and freestyle. The findings contributed to answering the first aim of this thesis, identifying the most commonly prescribed freestyle drills. While the single-arm drill was identified as the most prescribed freestyle drill, this thesis focused on drills commonly prescribed with the key goal to improve or condition upper-limb kinematics. The *Long Dog* and *Polo* drill were identified as two of the most commonly prescribed upper-limb freestyle drills. The results from Study One (Chapter 3) revealed how these drills were typically applied in training. This allowed for the action fidelity of the two commonly prescribed upper-limb drills to be tested in Study Two and Three (Chapter 5 and 6) under representative experimental protocols to those prescribed by coaches in training.

Chapter 4: Methodology of 3D Kinematic Assessment in Swimming

4.1 Introduction

The complexities and processes associated with the 3D kinematic analysis of the freestyle swimming stroke have been detailed in Chapter 2, section 2.4.5.1, p. 41). A multiple camera setup and the use of the DLT method allows for 3D quantitative analysis. Considerations for 3D kinematic analysis include the camera type and setup, calibration (both internal camera parameters and photogrammetric), digitisation processes, 3D reconstruction, filtering and variable calculations.

Due to the extensive methodological procedures required for Studies Two and Three (Chapter 5 and 6), this stand-alone chapter detailed the procedures undertaken for the 3D analysis of freestyle swimming and specific drill-based tasks. The subsequent chapters (Chapters 5 and 6) provide a brief summary of the methods outlined in this chapter, along with the study-specific analysis methods.

4.2 Participants

Six elite freestyle swimmers (4 male, 2 female, age 19.67 ± 2.75 years, Fédération Internationale de Natation (FINA) points 844 ± 59) were recruited from the Victorian Institute of Sport (VIS) Swimming Program and voluntarily participated in the study. The selection criteria limited participants to higher skilled swimmers with well-established freestyle stroke characteristics (McCabe & Sanders, 2012; Nikodelis, Kollias, & Hatzitaki, 2005; Pyne, Trewin, & Hopkins, 2004). Characteristics of the elite freestyle participants are presented in Table 4.1. To be eligible, participants had to: (a) attend national and international level competitions on a regular basis, (b) have a minimum of two years specialised in their chosen distance as a freestyle swimmer and (c) have no injuries nor be in the process of recovery at the time of testing.

Table 4.1 Participant information and general physical characteristics.

Participant	Gender	Age (yrs.)	Height (cm)	Mass (kg)	Distance specialisation
SW1	Male	17	185.80	73.00	Sprint
SW2	Female	16	166.50	70.38	Middle
SW3	Male	19	190.90	84.00	Long*
SW4	Male	24	196.10	88.00	Sprint
SW5	Female	20	178.00	77.30	Middle
SW6	Male	22	190.00	90.10	Long

Sprint = 50 - 100m, Middle = 200 - 400m and Long ≥ 400 m
*Open water and distance specialist.

Ethical approval to conduct the study was sought and provided by the Victoria University Human Research Ethics Committee (see Appendix B – Participant information and consent). Members of the research team approached and recruited the participants, in person, informing them of the nature of the study. Participants, having consulted and received approval from their coach, agreed upon convenient times to perform the given testing procedures. All participants received a full explanation of the purpose of the study and protocols involved and (or a parent/guardian when a participant was under 18 years old) provided signed written consent prior to the testing procedures. To secure confidentiality, participants were assigned a pseudonym label (e.g., SW1 – SW6). Throughout the thesis, the pseudonym label assigned to each individual swimmer will be used rather than the swimmers' name.

All participants wore polyester training swim wear, as normally worn in training. To enable the identification and tracking of anatomical landmarks, nineteen black markers (36 mm in diameter) were affixed on the right and left side of each participant (Figure 4.1). Pilot investigations revealed that black markers gave the best contrast and could most easily be seen in the underwater environment. Marker sites included the tip of the third distal phalanx, styloid process of the lunar and radius, olecranon process of the ulna, greater tubercle of the humerus, greater trochanter, lateral epicondyle of the femur, lateral malleolus, fifth metatarsophalangeal joint and first interphalangeal joint. To minimise errors in subsequent calculations of variables, the placement of all the markers were carefully applied to the skin corresponding to the axis of the particular joint (Sanders, Chiu, et al., 2015). Further, the markers were made from medical-grade, water-proof tape in order to reduce the effect of additional drag on swimming performance (Washino, Mayfield, Lichtwark, Mankyu, & Yoshitake, 2019)

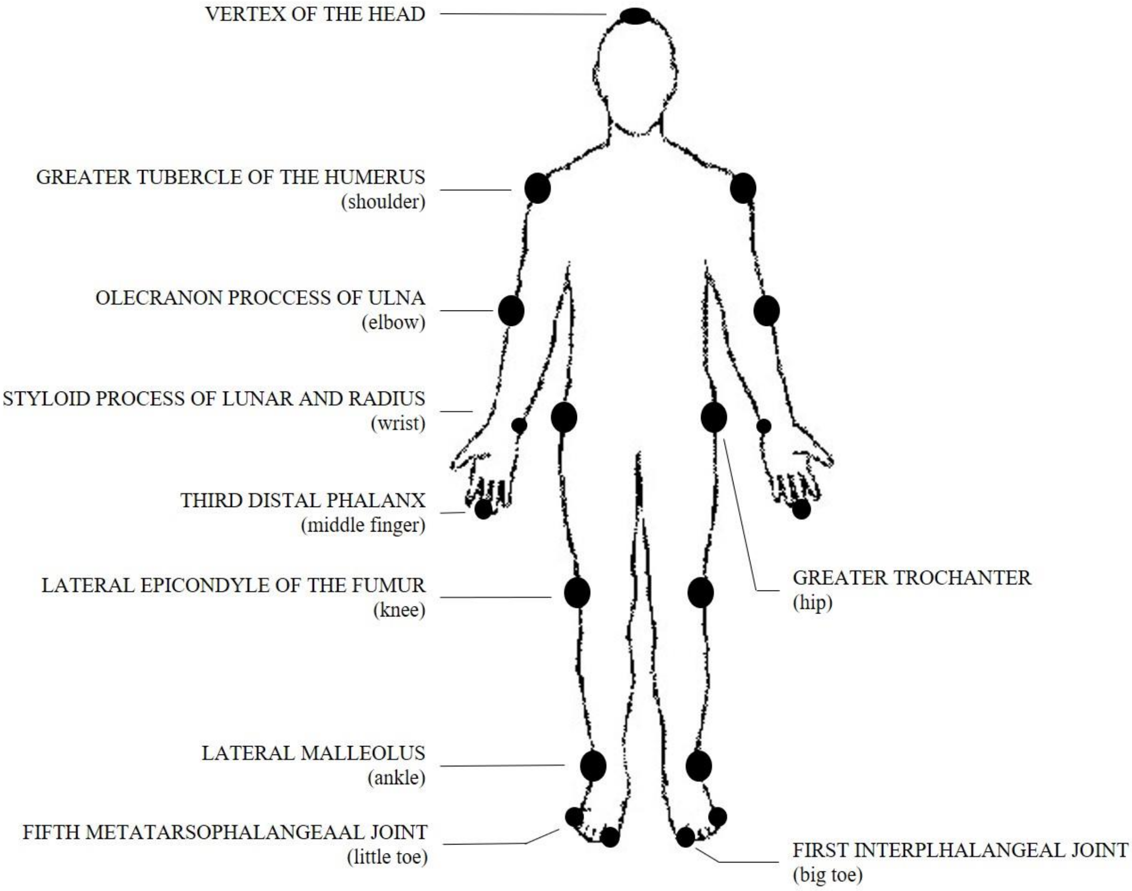


Figure 4.1 Model representation (anatomical position) of the marker locations used during the swim trials.

4.3 Experimental design

4.3.1 Swimming pool details

The testing procedures took place in a four-lane 25 m level deck, indoor pool (1.20 – 1.90 m deep). The average water temperature was 26°C and the outside pool temperature was 28°C with a humidity of 48%. Only one swimmer at any time was permitted in the pool during the testing procedures to minimise wave turbulences and prevent any possible interference with camera views. Wave turbulences were also minimised due to the nature of the level deck pool which displaces excess water into the overflow channel perimeter.

4.3.2 Camera setup and settings

The swimming movement was captured using four above- and four below-water stationary cameras (SwimPro®, Newcastle, Australia), operating at a sample frequency of 30 Hz. Generally, filming underwater is problematic and introduces additional errors to those associated with analysis of motion on dry-land (Kwon, 1999). However, the stationary cameras used were specially designed for the aquatic environment. This enabled them to be positioned directly underwater which was expected to reduce optical refraction and distortion effects (Kwon, 1999; Kwon & Casebolt, 2006). Image synchronisation was obtained using a pair of LED lights under and above the water surface, visible in each camera's field of view.

The cameras were mounted onto four separate custom-made bracket frames enabling one camera to be mounted above-water and one camera to be mounted below the water surface (Figure 4.2). Brackets were designed and engineered to allow them to be positioned in the pool using the existing fixings. The steel structure and fixtures enabled the height and angle of each camera to be adjusted, yet ensured that the cameras remained in position once fixed. The design specification of the camera frames came through pilot testing and experimentation at the swimming pool. The manufacture process was assisted by the engineering company Change Parts Pty Ltd. and funded by Victoria University. Table 4.2 details the specific camera models used per camera frame and approximate depths below/under the water surface. While the camera models used varied per camera frame, each camera was adjusted to the same shutter speed, resolution and focal length settings. Figure 4.3 illustrates the position of the four camera bracket frames (labelled Camera Frame 1 – Camera Frame 4, including the calibration frame) used throughout the 3D experimental procedures. Refer to section 4.3.3 (p. 97) for more details regarding to the construction of the calibration frame.

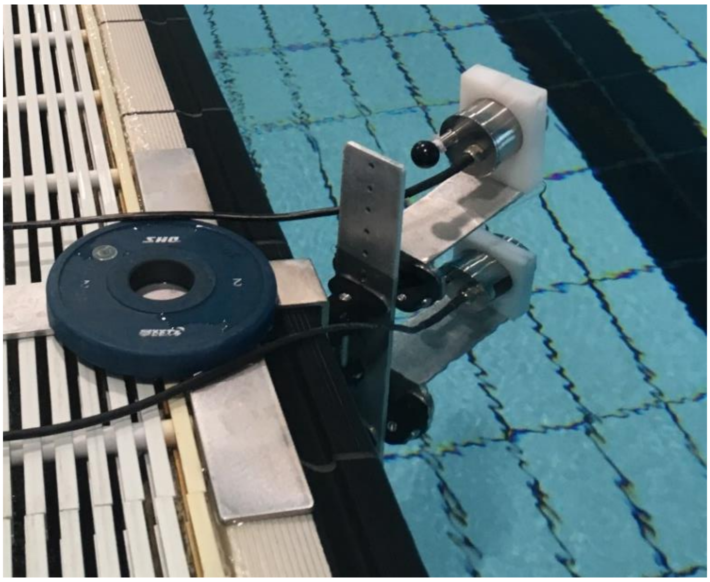


Figure 4.2 Stationary cameras mounted onto custom-made bracket frame.

Table 4.2 Specific camera type per camera frame.

	Camera name (position)	Approximate depth above-/below-water surface (m)
Camera Frame 1	ClawCam (above-water)	0.10
	FloorCam (below-water)	0.40
Camera Frame 2	ProX (above-water)	0.15
	FloorCam (below-water)	0.35
Camera Frame 3	WallCam (above-water)	0.15
	PlatinumPlus (below-water)	0.35
Camera Frame 4	ClawCam (above-water)	0.10
	WallCam (below-water)	0.40

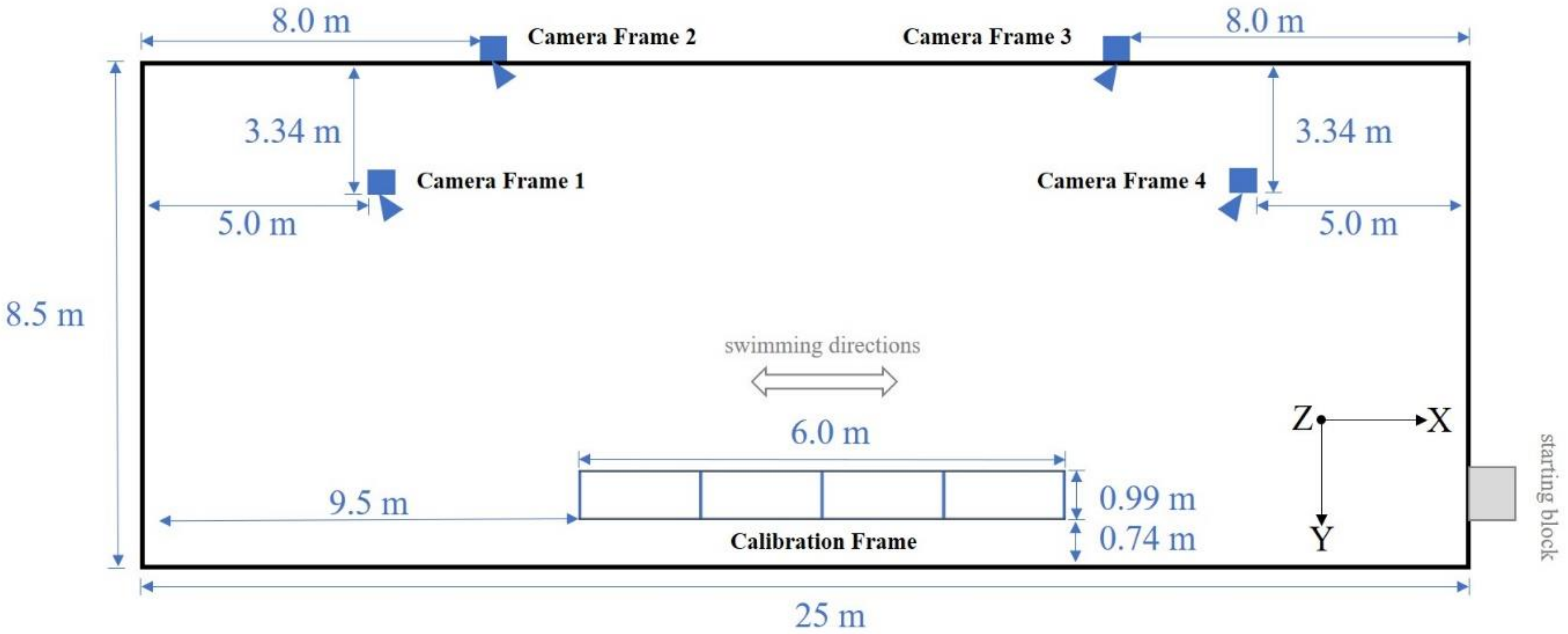


Figure 4.3 Experimental setup and calibration frame position.

Two SwimPro® iQ2 analysis recorder systems, stored the recorded footage for each camera. The electric shutter speed and resolution for each camera were adjusted via the analysis recording system to 1/250 seconds and 720p, respectively. While the focal length of the cameras could not be adjusted, the cameras were positioned so that a minimum of one complete stroke cycle could be captured within the pre-calibrated space. Specifically, the position of each camera was adjusted to ensure that a volume approximately 8.0 m long could be captured, extending at least 1.0 m beyond each side of the 6.0 m long calibration frame on the x-axis (Figure 4.4). Figure 4.5 and 4.6 illustrate an example of the field of view recorded by one of the above- and underwater cameras.

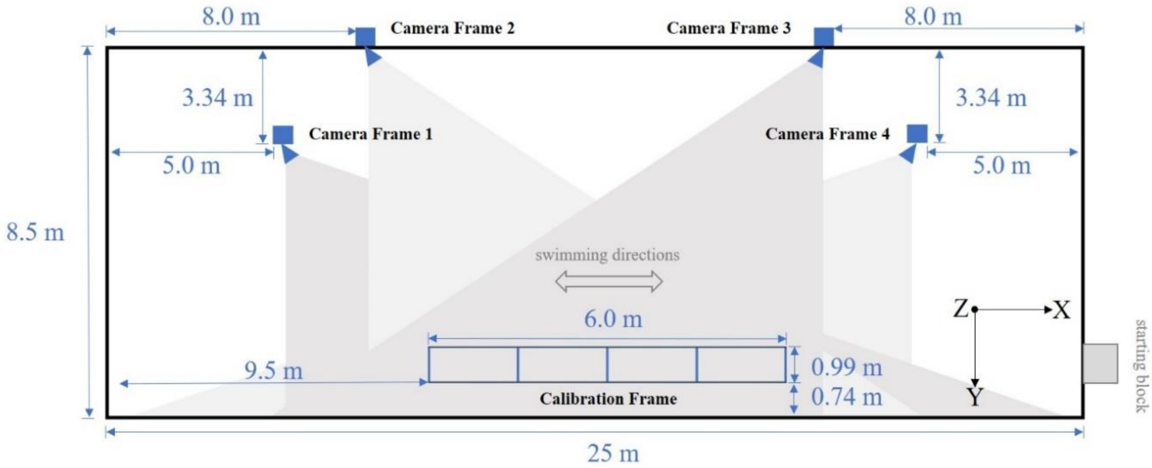
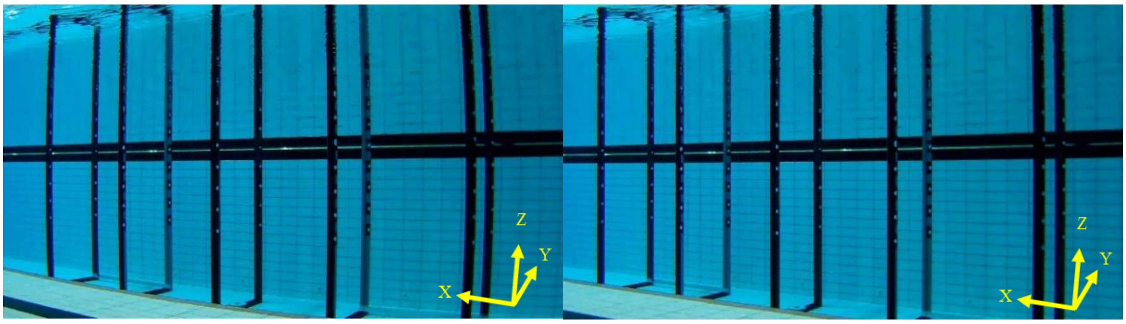


Figure 4.4 Approximation of cameras’ field of view.

Figure 4.5 Above-water camera view of the calibration frame position in the pool (from ProX camera, Camera Frame 2).

Figure 4.6 Underwater camera view of the calibration frame position in the pool (from FloorCam5 camera, Camera Frame 2).

The cameras had wide-angle (fish-eye) lens which caused tangential and radial distortions to the image. If left uncorrected these image distortions result in inaccurate geometric measurements during data processing (Kannala et al., 2007; Kwon & Casebolt, 2006). To correct the image distortions, a method referred to as explicit calibration was used. This method involves slowly moving a planar chequered board grid (squares of know size) in front of the camera (Zhang, 1998). The still images of the chequered board grid, placed at different orientations in front of the camera, were then imported into a developed algorithm (available as a Matlab (MathWorks, Natick, MA, USA) toolbox) in order to obtain the intrinsic camera parameters for each camera, separately (Beardsley et al., 1992; Remondino & Fraser, 2006; Silvatti et al., 2013). The intrinsic camera parameters included the focal length, principal point, radial distortions, tangential distortions and pixel size. Using the 'Tracking' function in the a custom-built Matlab toolbox, Cinalysis (Elipot, Dietrich, Hellard, & Houel, 2010a), these intrinsic camera parameters were applied to each video file in order to correct the image distortions prior to any further data processing. The Cinalysis program was designed specifically for 3D analysis in swimming and has been used in previous research (Elipot et al., 2010a; Papic, Sanders, Naemi, Elipot, & Andersen, 2020). Recording a space of at least 8.0 m long (in the *x*-axis) ensured that no calibration points within the calibration frame were lost through the correction of the lens distortion. Figure 4.7 illustrates the correction of the FloorCam5 camera lens distortions.



BEFORE lens distortion correction AFTER lens distortion correction

Figure 4.7 Example of camera view before and after lens distortion correction.

4.3.3 Calibration frame and calibration of 3D space

A calibration frame was constructed for this study so that at least one stroke cycle could be analysed (de Jesus et al., 2015; Psycharakis et al., 2005) (Figure 4.8).The coordinates from the 3D calibration space are used as part of the 3D reconstruction process (Abdel-Aziz & Karara, 1971; Dadashi et al., 2013; Payton, 2008).

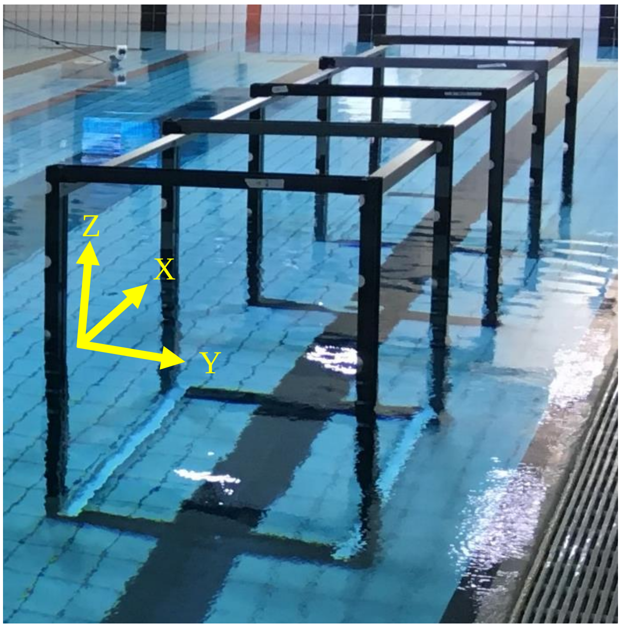


Figure 4.8 Calibration frame for 3D analysis.

The 3D calibration frame was a rectangular prism with the following dimensions: 6.0 m length (*x*-axis), 1.0 m width (*y*-axis) and 2.5 m height (*z*-axis). The calibration frame was positioned on the bottom of the pool with the x-axis aligned horizontally with the swimming direction and the *y*- and *z*- axis representing the lateral and vertical position, respectively (Figure 4.8). The frame was divided into five sections made of 100 x 44 mm aluminium tubing. Each frame was connected together by aluminium angle supports on the bottom and top of the structure. The material of the frame was selected on the basis of its high flexural stiffness relative to its weight to minimise distortion of the frame during research and storage in the pool environment (Psycharakis et al., 2005). The entire frame and joints were manufactured with fine tolerance to ensure that when the structure was positioned on the bottom of the pool, all adjoining sides of the frame were orthogonal.

Seventy black, circular markers (36 mm in diameter) were attached, with 250 mm separation in the z- axis. This was done to create a 6.0 x 1.0 x 1.5 m^3 calibration volume, where 0.5 m was above the water surface and 1.0 m was below the water on the vertical axis. The accuracy of the marker positions was validated using a seven–camera motion analysis system (T40 series, Vicon Nexus, Oxford, UK) in an indoor area. The cameras (mounted at 1.5 ± 0.9 m) were placed in an arc around the frame and reflective markers where attached to the centre of each of the marker locations on the frame (Figure 4.9). The 3D coordinate's accuracy of the markers was 0.03 mm for *x*, *y* and *z*. Figure 4.5 and 4.6 (p. 95) shows an above- and underwater view of the 3D calibration frame positioned in the water.

Figure 4.9 Marker location validation using seven-camera motion analysis system.

Before each testing session, the calibration frame was placed into the swimming pool and videoed simultaneously by the four above- and four underwater cameras. No one was permitted to be in the water during this capture. This ensured that there were no disturbances to the water that could potentially interfere with the calibration process. The calibration frame was then removed from the pool and no further adjustments were made to the camera position or settings.

For the 3D reconstruction, the 3D calibration space was divided into two areas: above- and underwater. The waterline was assigned as the origin where the z-axis coordinates were positive above waterline and negative below the waterline. The dimensions of the above-water calibration volume were 6.0 m length (*x*-axis), 1.0 m width (*y*-axis) and 0.5 m height (*z*-axis). The four above-water cameras captured the above-water calibration volume which contained 30 calibration points. Similarly, the dimensions of the underwater calibration volume were 6.0 m length (*x*-axis), 1.0 m width (*y*-axis) and 1.0 m height (*z*-axis). The underwater calibration frame contained 50 calibration points and was captured by the four below water cameras. The 10 calibration points directly in the centre of the waterline were captured by both the above- and below-water cameras, creating an overlap between the two calibration areas. The position of the cameras around the calibration frame ensured that all the markers on the calibration frame were clearly distinguishable. This clear marker detection not only facilitated to increase the accuracy during digitisation but more importantly, increased the accuracy of the subsequent 3D analysis procedures. The overall 3D space mean (RMS) reconstruction error and maximal reconstruction error results for the two calibration areas is shown in Table 4.3 and 4.4, respectively.

Table 4.3 Mean RMS errors for calibration volume areas.

Calibration area	No. calibration points	RMS errors (mm)			
		X	Y	Z	Mean
Above-water surface	30	4.7 ± 0.8	3.6 ± 0.8	4.9 ±0.6	7.8 ± 0.6
Below-water surface	50	4.5 ± 0.4	3.8 ± 0.3	6.2 ± 0.6	8.6 ± 0.5

Table 4.4 Mean maximal errors for calibration volume areas.

Calibration area	No. calibration points	RMS errors (mm)			
		X	Y	Z	Mean
Above-water surface	30	11.7 ± 2.1	8.4 ±1.8	11.8 ± 1.6	14.5 ± 2.0
Below-water surface	50	9.4 ± 0.4	9.1 ± 1.6	15.5 ± 2.1	16.4 ± 1.5

The RMS reconstruction error and maximal reconstruction error values were calculated using Equations 4.1 and 4.2 given by Kwon and Casebolt (2006).

$$\varepsilon = \sqrt{(Xk - Xr)^2 + (Yk - Yr)^2 + (Zk - Zr)^2} \qquad [\mathbf{4.1}]$$

$$\varepsilon_{RMS} = \sqrt{\frac{1}{n}\sum \varepsilon^2} \qquad [\mathbf{4.2}]$$

where Xk, Yk, Zk are the known object-space coordinates, Xr, Yr, Zr are the reconstructed object-space coordinates, ε is the reconstruction error for a given control point and ε_{RMS} is the overall reconstruction error.

The calculated RMS reconstruction error and maximal reconstruction error values were similar and even lower than those reported in previous swimming studies (de Jesus et al., 2015; Psycharakis et al., 2005) (Table 4.3 and 4.4). For example, for a

6.0 x 2.5 x 2.0 m^3 calibration volume, de Jesus et al. (2015) reported mean RMS errors of 15.9 ± 6.6 and 13.3 ± 6.7 for the above- (38 calibration points) and underwater (58 calibration points) calibration area, respectively. Using such a large calibration volume minimised the possibilities of extrapolation as a minimum of one stroke cycle could be recorded, increasing the accuracy of measurements. For this reason, a similar calibration volume was employed in this study where the errors within the 3D reconstruction accuracy were considered low and acceptable for the subsequent swimming kinematic analysis.

4.4 Experimental procedures

The drill selection and testing protocol were informed by the qualitative findings from Study One (Chapter 3) whereby 20 elite Australian swimming coaches where interviewed in regards to the skill development and the prescription of commonly prescribed freestyle drills (Brackley, Barris, Tor, & Farrow, 2020). Specifically, it was reported that coaches generally prescribed drills in 25 m or 50 m blocks before incorporating freestyle swimming again.

Data collection for each participant required one, two-hour session and took place in the pre-calibrated pool (as detailed in the section 4.3, p. 90). Participants performed two freestyle drills, *Polo* and *Long Dog*, in randomised order. The testing protocol for each drill required participants to swim total of 300 m broken into 2 x 25 m drill then 2 x 25 m laps of freestyle swimming. Table 4.5 provides a description of each drill and the key task goals. The testing protocol was deemed sufficiently representative of the execution of drills in the training environment given the retrospective observations of training and the qualitative data from Study One (Chapter 3). Further, all participants performed the two drills regularly within their individualised training programs.

Table 4.5 Freestyle drill tasks, description and testing protocol.

Drill	Task goal	Description	Distance (m)*
Polo	• Catch position (hand entry). • Stroke rhythm (arm coordination).	‘Head above-water’ freestyle Freestyle swam with head above water, maintaining a strong flutter kick.	300
Long dog	• Catch position (hand entry). • Underwater recovery (pull phase). • Body rotation. • Trunk alignment.	‘Underwater recovery’ freestyle Freestyle swam with no traditional above water arm recovery phase, starting with one arm extended in front of the head.	300

*swam as 2 x 25 m of drill followed by 2 x 25 m of freestyle and so on.

Prior to the testing procedures, nineteen black anatomical markers (36 mm in diameter) were affixed to the participant’s skin in locations detailed in section 4.2 (p. 88). Lane ropes were removed to prevent any occlusions of the swimming movements. Prior to testing participants were given time to familiarise themselves with swimming along the centre of the black tiles on the bottom of the pool. Participants then performed their individualised warm-up which consisted of both dryland exercises and low- to moderate-intensity aerobic freestyle swimming (no drills performed). The instructions given to each participant was to perform the drill and swim trials as they would in training, self-paced and taking breaks as required. All swim trials started at the ‘start block’ end of the pool and were initiated in the water from a push start (McCabe et al., 2011; Psycharakis & Sanders, 2008; Seifert, Chollet, et al., 2004). Unlike training, however, participants were further instructed to avoid performing the traditional tumble turn at the end of each 25 m lap. These instructions were to eliminate any possible influence that the tumble turn and/or dive could have on the stroke kinematics (Takeda, Ichikawa, Takagi, &

Tsubakimoto, 2009; Veiga & Roig, 2017). No additional feedback or instructions were given on their performance.

4.5 Data processing

Following data collection, the camera recordings of the swim trials were transferred from the analysis recorder system onto a separate hard drive. The files were converted to audio/video interleaved (AVI) files and then each swim trial was synchronised and cropped into 10 second clips using the open-access 2D motion analysis program Kinovea (www.kinovea.org, version 0.8.15). The rationale behind cropping the video files into 10 second clips per 25 m swim trial was to ensure that all movement within the pre-calibrated space was captured. All video files were checked to ensure that the duration and start time were the same for each of the eight camera views per swim trial.

The Cinalysis 'Tracking' and 'Calibration' function were used to create two calibration files, one for the above-water and one for the underwater camera views. These files identified the number and position of the calibration points, including the space reconstruction accuracy of the calibration points (discussed in section 4.3.3, p. 97). Specifically, using the Cinalysis 'Tracking' function the lens distortion was corrected (discussed in section 4.3.2, p. 91) and then the marker points on the calibration frame were manually digitised to obtain the video pixel (u, v) coordinates for each marker. This procedure was performed for all eight camera views, creating eight separate output files. The calibration points were digitised in the same order for both the above- and underwater camera views (Figure 4.10 and 4.11)

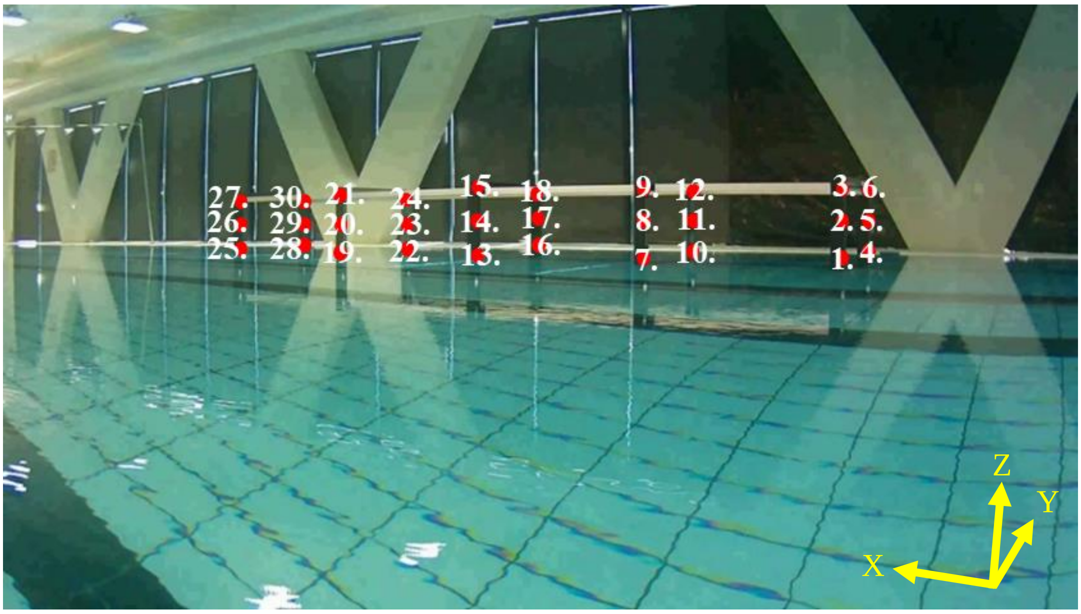


Figure 4.10 Order in which the calibration points were digitised for each of the above-water camera views.

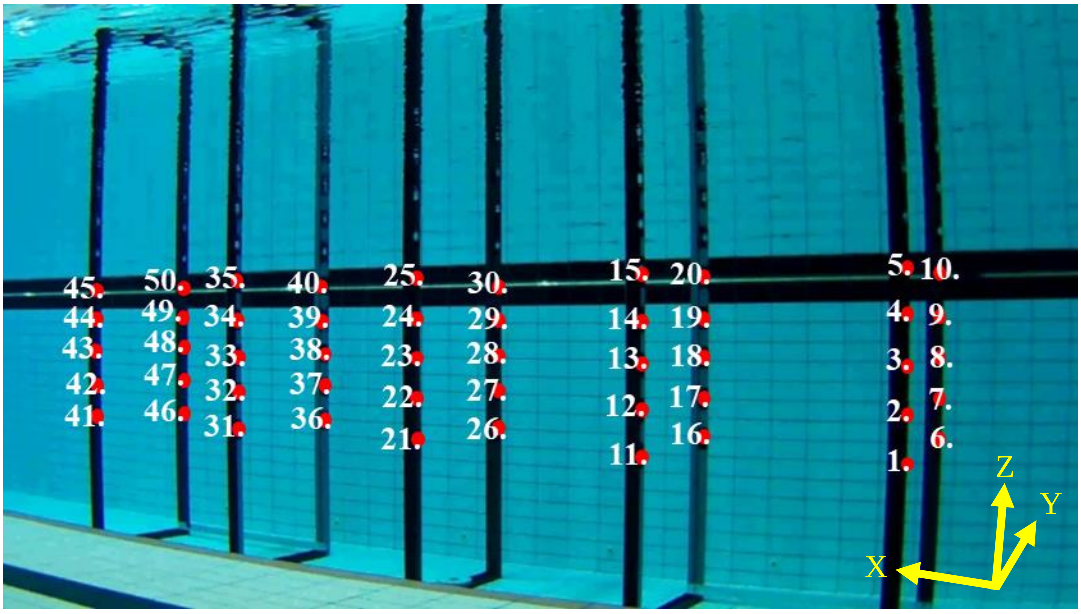


Figure 4.11 Underwater camera view of the order in which the calibration points were digitised.

For the underwater calibration area, the known object-space coordinates (*x*, *y*, *z*) and the four output files from the video pixel coordinates, for the 50 points underwater calibration points, were imported into the Cinalysis 'Calibration' function (Elipot et al., 2010a). The standard Direct Linear Transformation (DLT) 3D algorithm was used to determine the reconstructed object-space coordinates (*x*, *y*, *z*), the reconstruction error for each calibration point, the overall reconstruction error and the four camera coefficients. These values where then exported into a single output file. The same procedures and 3D configurations were repeated for the four output files from the above-water calibration points. Table 4.3 and 4.4 (p. 100) summarises the overall reconstruction error and the maximum reconstruction error for both the above- and underwater calibration areas.

4.5.1 Digitising swim trials procedure

The freestyle and drill swimming movement were analysed kinematically using one complete stroke cycle for each of the twelve 25 m swim laps per drill protocol and swimmer. One stroke cycle was defined as the period between the entry and re-entry of the same hand. Depending on the swimming direction, either the right or left side of the swimmer was digitised as symmetry could not be assumed for freestyle swimmers. The trials analysed consisted of a combination of right- and left-handed stroke cycles both between and within participants.

The camera recordings of the swim trials were imported into the Cinalysis 'Tracking' function where the lens distortion was corrected (discussed in section 4.3.2, p. 91) and then the visible anatomical landmarks were manually digitised for each of the eight above- and below-camera views. For this study, only the tip of the third distal phalanx, styloid process of the lunar and radius, olecranon process of the ulna, greater tubercle of the humerus and the greater trochanter were digitised. For anatomical landmarks not visible in a particular frame, the Cinalysis 'Tracking' function allowed points to be 'skipped' rather than 'guessing' the anatomical landmark. Once the anatomical landmarks were digitised for the stroke cycle visible within the pre-calibrated space, the video pixel (*u*, *v*) coordinates and time stamps corresponding to each one of the anatomical landmarks were exported into a single 'tracking' file. It should also be highlighted that no below water calibration points or anatomical landmarks were digitised from above-water views and vice versa, with the exception of the 10 markers directly in the centre of the waterline which were visible from both the above- and underwater camera views.

Once all eight camera views were digitised for the particular swim trial, the DLT equations were applied to the data from the eight 'tracking' files to produce the 3D coordinate data (*x*, *y*, *z*) for the above- and underwater camera views. The transformed data displayed the raw displacement, velocity and acceleration data (*x*, *y*, *z*) for all digitised landmarks into a single file. The file contained three separate tabs for the displacement, velocity and acceleration data, respectively.

4.5.2 Filtering

Landmarks not visible in a particular frame on more than two camera views resulted in missing 3D coordinates as the DLT equations requires at least two video pixel (*u*, *v*) coordinates for each landmark. Missing 3D coordinates were interpolated using cubic spline interpolation. This method has been used in previous swimming biomechanics research (Callaway, Cobb, Jones, Arellano, & Griffiths, 2009; Silva, Salazar, Borges, & Correia, 2011; Suito et al., 2017). Despite the many interpolation approaches that exist (e.g., linear, high order polynomial functions and linear spline), the cubic spline interpolation is believed to give the "smoothest" and best (in a least square sense) approximation of "reading between the lines" of digital signal data (Hou & Andrews, 1978; Schafer & Rabiner, 1973). This interpolation process was applied to the transformed data prior to the filtering process using a custom-built Matlab script.

A second-order Butterworth filter (Winter, 1990) was used to filter the raw data. Both Butterworth filters and Fourier series have been used in swimming analysis and are regarded appropriate when analysing cyclical movement patterns (Gonjo et al., 2019; McCabe & Sanders, 2012; Naemi et al., 2010; Schreven, Beek, & Smeets, 2015). The Butterworth filter operates by removing noise through a rational choice of a filter cut-off frequency (Bartlett, 2014). For movements such as swimming, Bartlett (2014) recommended lower cut-off frequencies of between 4 and 8 Hz. However, Schreven et al. (2015) cautioned that the difference in motion between body segments and participants may lead to differences in optimal cut-off frequencies for each anatomical marker and 3D coordinate. In this study, the cut-off frequency ranged between 3 and 8 Hz and was chosen through residual analysis where the 3D coordinate data (*x*, *y*, *z*) of each digitised landmark was filtered separately (Bartlett, 2014; Schreven et al., 2015; Winter, 2009). An example of specific cut-off frequencies determined through residual analysis for one participant trial are presented in Table 4.6. The selection of each cut-off frequency comprised of finding the breakpoints in the residual curve. A conservative approach was taken meaning that a higher cut-off frequency was selected to allow an amount of noise through the filter in order to avoid losing valuable data (Winter, 2009). Visual inspection of the data confirmed that the smoothed data did not remove valuable maxima and minima data points.

Table 4.6 Cut-off frequencies determine through residual analysis for one participant trial.

SW1	**Finger**			**Wrist**			**Elbow**			**Shoulder**			**Hip**		
	x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
Cut-off Frequency (Hz)	4	7	5	4	5	5	4	7	4	3	4	4	3	6	4

4.5.3 Calculation of variables

A custom Matlab script was written and used for all variable calculations in this study. The interpolated and filtered displacement and velocity data (*x*, *y*, *z*) were imputed into the Matlab script.

4.5.3.1 Swim performance parameters

Key performance parameters relating to horizontal swimming velocity (SV) are stroke length (SL), stroke rate (SR) and stroke index (SI) (Arellano, Brown, Cappaert, & Nelson, 1994; Chollet et al., 1997; Seifert, Boulesteix, et al., 2005). A description of how these parameters were determined are detailed in Table 4.7 where a stroke cycle refers to the entry and re-entry of the same hand during the cyclic freestyle movement.

Table 4.7 Calculation definitions of key performance parameters.

Performance parameters	Calculation definition
Swimming velocity (SV) (m/s)	The mean horizontal displacement of the hip (SL) multiplied by the inverse of time to complete one stroke cycle.
Stroke length (SL) (m)	Horizontal displacement of the hip during a complete stroke cycle (Gourgoulis et al., 2014).
Stroke rate (SR) (Hz)	The inverse of time taken to complete a stroke cycle.
Stroke index (SI) (m^2/s)	The mean horizontal displacement of the hip (SL) multiplied by the average horizontal swimming velocity.

The greater trochanter (hip) was used to estimate the centre of mass during one stroke cycle (Gourgoulis, Aggeloussis, Vezos, et al., 2008; Gourgoulis et al., 2014). Evidence within the literature has confirmed that the use of the hip instead of the centre of mass to estimate SV has a tendency to either under- or overestimate velocity values (Fernandes, Ribeiro, Figueiredo, Seifert, & Vilas-Boas, 2012; Figueiredo, Boas, Maia, Gonçalves, & Fernandes, 2009; Psycharakis & Sanders, 2009). However, the specific anatomical landmarks digitised for this study limited the centre of mass to be estimated. Consequently, when using the hip as a measure of SV and/or displacements, Fernandes et al. (2012) recommended that the hip point error magnitude needs to be taken into consideration in the interpretation of the results. As the sampling frequency of the cameras used in the current study was 30 Hz, the precision in the determination of the beginning and the end of each phase could not be less than 0.033 s (Gourgoulis et al., 2014).

4.5.3.2 Quantifying phases with the stroke cycle

The stroke cycle in freestyle swimming is typically separated into four phases (detailed in Chapter 2, section 2.4.4, p. 34) (Chollet et al., 2000; de Jesus et al., 2012). In this study the stroke cycle phases are identified as entry and catch, pull, push and recovery (Chollet et al., 2000; Seifert, Chollet, & Rouard, 2007; Sobrino et al., 2017). The phases within the stroke cycle are defined further in Table 4.8. In the presentation of results between freestyle and drill swimming, the stroke cycle time and the duration of the different phases was expressed as a percentage of the stroke cycle.

Table 4.8 Definition of phases identified within stroke cycle.

Stroke cycle phases	Definition
Entry	The first frame the finger breaks the water surface, on initial hand entry, to the first frame the finger begins to move horizontally backwards.
Pull	The first frame when the finger begins to move horizontally backwards until the finger is vertically aligned with the shoulder joint.
Push	The first frame when the finger is vertically aligned with the shoulder joint until the end of the horizontal backwards movement of the finger. This is close to when the finger exits the water.
Recovery	The first frame of the end of the horizontal backwards movement of the finger until the same finger re-enters the water.

4.5.3.3 Hand displacement and velocity

The vertical motion of the cyclic upper segment pathway was analysed by calculating the maximum displacement (m) of the third distal phalanx finger, in the *z*-axis, throughout the underwater phase of the stroke cycle. The maximum, minimum and range of motion were determined within the particular underwater stroke phase. The time corresponding to the maximum and minimum displacement were attained as both real time and percentage points relative to the commencement of the stroke cycle.

The lateral motion of the cyclic upper segment pathway during the underwater phase of the stroke cycle was calculated as the absolute range of motion of the third distal phalanx finger, styloid process of the lunar and radius (wrist) and olecranon process of the ulna (elbow) in the y-axis. The time corresponding to the maximum and minimum displacement were also attained as both real time relative to the commencement of the stroke cycle and percentage points of the stroke cycle.

4.5.3.4 Elbow flexion/ extension angle

The elbow flexion/extension angle, on both the right and left side of the participants, was quantified using the method described by McCabe et al. (2011). Specifically, the elbow angle was calculated as the arc-cosine of the dot products of the upper arm and lower arm unit vectors (Equation 4.3).

$$\theta = \text{acos}\left(\frac{a \cdot b}{|a||b|}\right) \qquad [\mathbf{4.3}]$$

where $|a||b|$ is the length of vector *a*, upper arm (wrist to elbow), multiplied by the length of vector *b*, lower arm (wrist to elbow); and $a \cdot b$ is the dot product of vectors a and b.

For this study, the elbow angle was quantified at four instances within the underwater stroke cycle: (i) hand entry, (ii) beginning of finger moving horizontally backwards, (iii) finger vertically aligned with shoulder and (iv) end of backwards movement (McCabe et al., 2011). Further, the elbow angle ranges during the pull and push phases were quantified. Pull range was calculated as the elbow angle at the start of pull phase minus elbow angle at the start of push phase. Push range was calculated as the elbow angle at the start of recovery phase minus elbow angle at the start of push phase. The quantitative assessment of the elbow angle during the particular underwater stroke phases provided a useful way to see how this variable is influenced between freestyle and drill swimming relative the task goal of the particular drill.

4.5.3.5 Shoulder and hip motion

One of the task goals of the *Long Dog* drill progression was to promote body rotation. To measure body rotation (e.g., shoulder and hip roll) using a motion capture approach requires a swimming pool setup that enables both sides of the swimmer to be captured, simultaneously. As only the right and left side of the swimmer could be captured separately with the current experimental design, the shoulder and hip motion in the z-axis were subsequently calculated as an alternative indicator.

The vertical motion of the shoulder, on both the right and left side of the participants, during the stroke cycle was analysed by calculating the vertical displacement of the greater tubercle of the humerus (shoulder). Similarly, the vertical motion of the hip, on both the right and left side of the participants, during the stroke cycle were analysed by calculating the vertical displacement of the greater trochanter (hip). The time corresponding to the maximum and minimum displacement were attained as both real time relative to the commencement of the stroke cycle and percentage points of the stroke cycle. Lastly, the velocity of the shoulder and hip, within each stroke phase, was obtained directly from the transformed velocity data (differentiated displacement data).

4.5.3.6 Trunk inclination

Trunk inclination was assessed in order to gain an indication of the effect drill swimming has on the swimmers' body alignment. The trunk inclination was calculated as the angle between the trunk and the horizontal plane within the particular underwater stroke phase under investigation. (Gourgoulis et al., 2014; Zamparo et al., 2009). The trunk segment was formed by the greater tubercle of the humerus ($S_{houlder}$) and the greater trochanter (H_{ip}) (Equation 4.4).

$$trunk\ inclination = arctan\frac{(S_{houlder}-H_{ip})_z}{(S_{houlder}-H_{ip})_x} \qquad [\mathbf{4.4}]$$

4.6 Digitising reliability

Two operators digitised the swim trials of the six participants. The operators received demonstrations and underwent training to gain familiarity and accuracy with the custom-built Matlab toolbox, Cinalysis (Elipot et al., 2010a; Sanders, Chiu, et al., 2015). To assess the intra- and inter-reliability (within and between operator reliability) of the two operators' digitising technique, a single stroke cycle (randomly selected) was digitised five times for all eight camera views (Osborough, Daly, & Payton, 2015). Digitising was conducted on separate days with no repeats of the same camera view on the same day. This ensured that reliability was not artificially improved by familiarity due to the practice effect of identifying the anatomical landmarks (Sanders, Gonjo, & McCabe, 2015).

4.7 Statistical analysis

To compare differences between freestyle and drill swimming for each variable, a paired t-test was used. As there were a large number of tests, the *p*-value was initially set at a confidence level of $p < 0.05$ and then adjusted using the Bonferroni–Holm correction (Harrison et al., 2020; Holm, 1979). Previous swimming studies have also used the Bonferroni-Holm correction to control for multiple comparison tests (Issurin, Pushkar-Verbitsky, & Verbitsky, 2014; Martens, Daly, Deschamps, Fernandes, & Staes, 2015). The Bonferroni–Holm procedure reduces the apparent significant of effects by adjusting the rejection criteria for each test. Specifically, the *p*-values are sorted from smallest to largest. Using Equation 4.5, the *p*-value was adjusted for each test. If the *p*-value was greater or equal to the adjusted *p*-value, then the *p*-value was not significant. However, if the *p*-value was smaller than adjusted *p*-value, than the *p*-value was declared significant.

$$p^{B-H} = \frac{\alpha}{n} \qquad \textbf{[4.5]}$$

Where $P^{B\text{-}H}$ is the adjusted *p*-value using Bonferroni-Holm correction, α is the initial *p*-value and n is the number of tests remaining.

Prior to comparative analysis, the normality of each calculated variable was checked using the Shapiro-Wilk test. As some variables were not normally distributed, the paired samples Wilcoxon test was used as a non-parametric alternative of the paired t-test for the statistical treatment of those variables (Harrison et al., 2020). All processed data were analysed using R studio (R Core Team, 2016) and kinematic data reported as mean values and standard deviations.

The effect size was calculated using Cohen's *d* to describe the magnitude of difference. The interpretation of the effect size for each variable was calculated in accordance to Cohen (1988) which evaluates the magnitude of differences between two means. Specifically, Cohen's *d* expressed mean differences between two groups in standard deviation units whereby if the calculated *d* equals zero, then the mean of the difference scores is equal to zero. As *d* deviates from zero, the effect size becomes larger. Accordingly, if the absolute value of Cohen's *d* was less than 0.2 it was considered a very small effect, 0.2 to 0.3 was considered as a small effect size, 0.3 to 0.5 was moderate and greater than 0.5 was considered a large effect.

Chapter 5: The Effect of Drill Swimming on Freestyle Kinematics: Group-based Analysis

This chapter is based on the following peer-reviewed journal article:

Brackley, V., Tor, E., Barris, S., Farrow, D. & Ball, K. (2020). The comparison of drill swimming on freestyle kinematics: Group-based analysis. *Currently under second round review*

5.1 Abstract

Practice tasks that decompose the skill into smaller components are routinely prescribed to improve biomechanical qualities for efficient and fast swimming. However, the key movement and performance characteristics expected to be improved when drill swimming have not been specifically assessed. The aim of this study was to compare the kinematics of full freestyle swimming with two commonly prescribed upper-limb drills - *Long Dog* and *Polo*. Six elite freestyle specialists swam a total of 300 m, for each drill, broken into two 25 m laps of drill then two 25 m laps of freestyle swimming. Three-dimensional (3D) kinematic characteristics were recorded by four above- and four below-water cameras. Anatomical landmarks were digitised and the direct linear transformation (DLT) algorithm was used to perform the 3D reconstruction. The following variables were calculated: average swimming velocity, stroke length, stroke frequency, stroke index, duration of stroke phases, upper-limb displacement, elbow angle, shoulder and hip vertical displacement and trunk inclination. Paired t-tests indicated that when performing the *Long Dog* drill, participants presented no significant differences in shoulder movement, trunk inclination and upper-limb motion in the pull phase of the stroke compared to freestyle ($p < 0.05$ and $d \geq 0.03$). When performing the *Polo* drill, participants displayed upper-limb kinematic characteristics to that encouraged for sprint-distance swimmers. It was also suggested the *Polo* drill could lead to higher stroke rate values and inter-arm coordination adaptations transferable to movement adjustments beneficial for race-pace freestyle. This study highlighted how drills influence key movement and performance characteristics of freestyle performance.

5.2 Introduction

Freestyle swimming is the fastest and most efficient form of human locomotion through the aquatic environment (Seifert, Boulesteix, et al., 2005; Skorski et al., 2014). Subsequently, the biomechanical literature is replete with empirical findings on the kinematic and kinetic features critical to the upper-limbs, lower-limbs and coordination of the freestyle stroke (Guignard et al., 2019; Sanders et al., 2017; Toussaint & Beek, 1992). While informative, there is surprisingly little biomechanical analysis that has examined the specific practice tasks prescribed to help develop the skills critical for freestyle performance in competition (Arellano et al., 2010; López et al., 2002). Further, key movement and performance characteristics expected to be improved by current swimming drills have not been assessed.

The freestyle stroke, also referred to as front crawl, is characterised by alternating overhead arm stroke phases and a number of near-vertical leg kicks (Carmigniani et al., 2019; Yanai & Wilson, 2008). In order to evaluate the stroke technique, segmental kinematics are typically divided into upper and lower limb coordination strategies (de Jesus et al., 2016; Deschodt et al., 1999; Mooney, Corley, Godfrey, Quinlan, et al., 2015). The upper-limb actions provide around 68% of the total propulsion, whereas the lower-limb actions contribute to around 31% (Morouço, Marinho, Izquierdo, et al., 2015; Swaine et al., 2010).. The greater contribution of the upper-limbs to total propulsion has led to extensive research on upper-limb kinematics where the motion of the hand is commonly considered the main instrument of propulsion (Chollet et al., 2000; Seifert, Chollet, & Rouard, 2007; Sobrino et al., 2017). For detailed analysis, the arm stroke cycle is typically categorised into four phases: (i) entry and catch, (ii) pull (constitutes the first part of propulsion), (iii) push (constitutes the second part of propulsion) and (iv) recovery (Chollet et al., 2000; Seifert, Chollet, & Rouard, 2007; Sobrino et al., 2017). Research has shown that while the hand motion has a direct influence on the streamlined body alignment and timing of body segments (Chollet et al., 2000; Maglischo, 2003; Sanders et al., 2017; Seifert, Chollet, & Rouard, 2007; Sobrino et al., 2017), the elbow flexion/extension angle influences the motion of the hand (Figueiredo, Nazário, et al., 2011; Figueiredo et al., 2012).

In addition to the biomechanical assessment of the trajectory of the arms, coordination between the arms have been extensively analysed through the Index of Coordination (IdC) measure (Chollet et al., 2000; Gourgoulis et al., 2014; Millet et al., 2002; Seifert, Chollet, et al., 2005). The IdC is a non-dimensional, timing-based measure that separates the beginning of the propulsive phase of one arm to the end of the propulsive phase of the other arm as a percentage of the mean duration of the arm stroke cycle (see Chollet et al. (2000) for detailed explanation). Three different coordination patterns have been identified: (i) opposition, continuity between the two arm propulsions where one arm begins the pull phase when the other arm is finishing the push phase, IdC = 0%; (ii) catch-up, time gap between the propulsive phase of the two arms, IdC < 0% and (iii) superposition, overlap between the propulsive phase of the two arms, IdC > 0% (Chollet et al., 2000; Chollet & Seifert, 2011; Gourgoulis et al., 2014; Seifert, Chollet, & Rouard, 2007).

To help swimmers improve upper-limb kinematics, qualitative data reported in Study One (Chapter 3) illustrated that the *Long Dog* drill is the most commonly mentioned drill used by elite Australian swimming coaches (Brackley, Barris, et al., 2020). The *Long Dog* drill has a similar resemblance to freestyle, however instead of the arm recovering above the water, the arm recovers underwater with the intention to help swimmers focus on the underwater phases of the stroke. (Figure 5.1 and 5.2). Specifically, the swimmer starts with the arm extended in front of the head and the other arm down at the side of the body. From the extended position, the swimmer pulls the extended arm down towards the hip, performing the pull and push phase of the freestyle stroke. Simultaneously, the other arm slides from the side of the body through the water into the extended streamline position over the head (no surface recovery phase). The task goal of the *Long Dog* drill is to improve or condition the body rotation, trunk alignment and the hand path within the pull phase of the freestyle stroke (Brackley, Barris, et al., 2020).

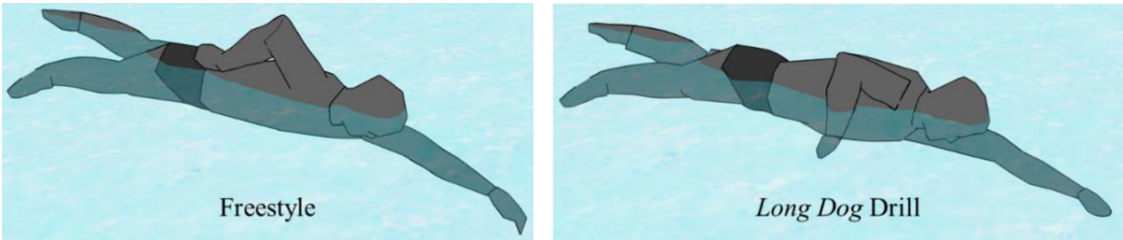


Figure 5.1 Illustration of freestyle and *Long Dog* drill swimming at a similar instant within the recovery phase of the stroke cycle. Notice that the hand remains in the water when *Long Dog* drill swimming.

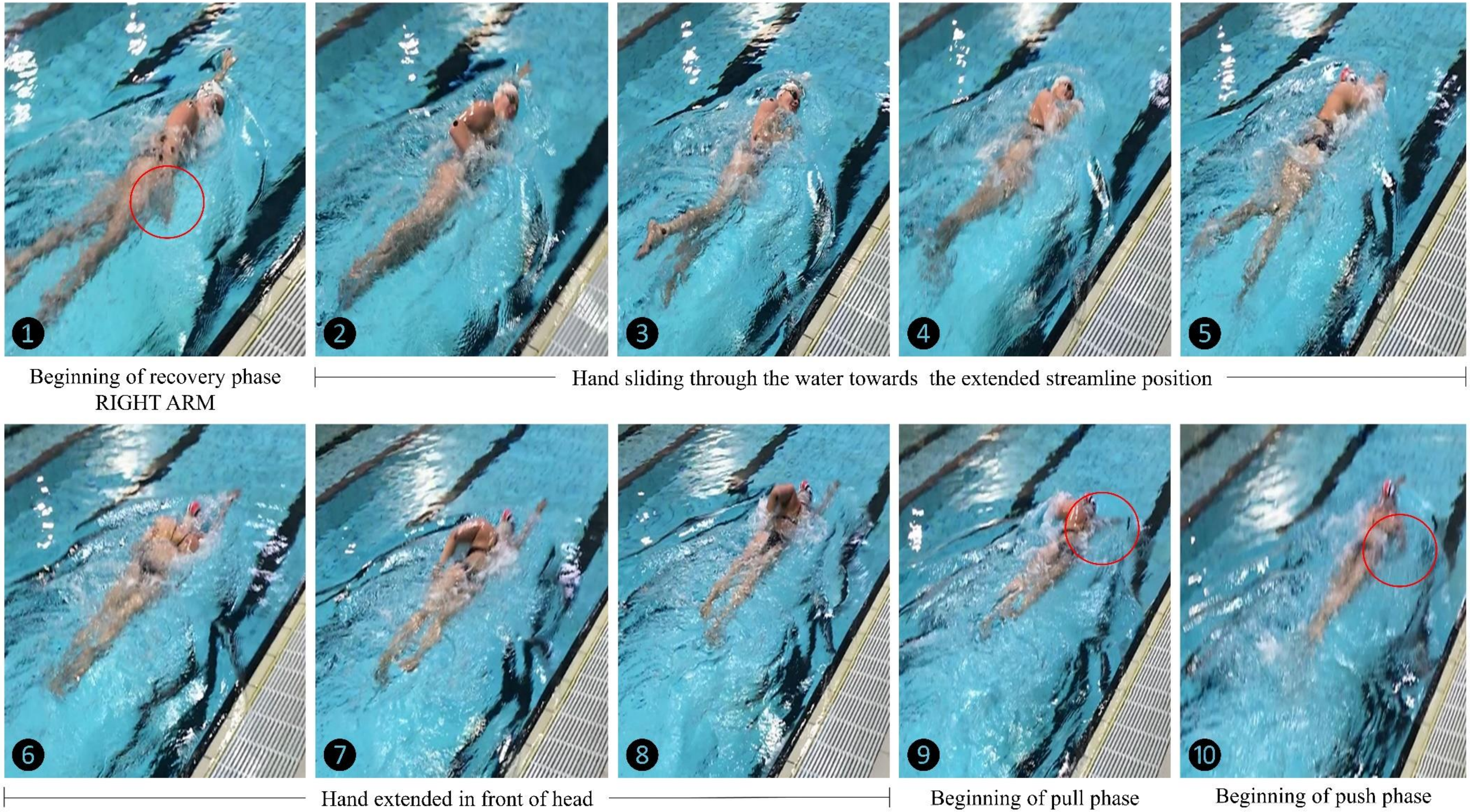


Figure 5.2 An example of the *Long Dog* drill. Notice that the hand remains in the water throughout the stroke cycle.

The *Polo* drill was identified as another commonly prescribed upper-limb freestyle drill in elite Australian swimming and resembles the movement of a polo player (Figure 5.3) (Brackley, Barris, et al., 2020). Typically, the task goals of the *Polo* drill are to improve the hand position and coordination during the entry and catch and pull phases of the stroke (Brackley, Barris, et al., 2020; Lucero, 2015). Biomechanical analysis has shown that these parameters are crucial for efficient and fast freestyle (Chollet et al., 2000; Seifert, Chollet, & Rouard, 2007; Sobrino et al., 2017), yet it is unknown how drills positively or negatively influence key freestyle parameters in the form of learning and performance.

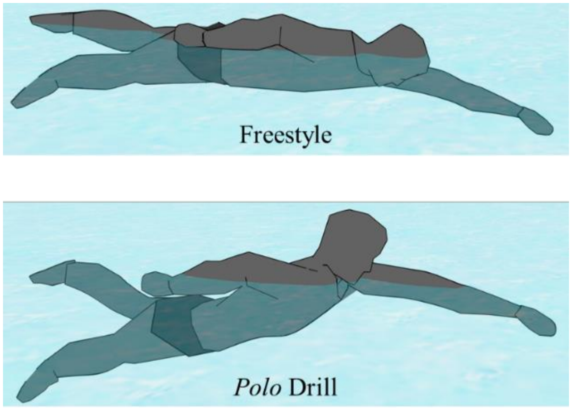


Figure 5.3 Illustration of freestyle and *Polo* drill swimming at similar instant within the recovery phase of the stroke cycle.

Traditionally, practice approaches have centred around tasks that (a) prioritise movement consistency (Davids et al., 1994; Seifert et al., 2013), (b) promote the invariant repetition of a single ideal movement pattern (Brison & Alain, 1996; Davids et al., 2017; Schmidt & Lee, 2011) and (c) decompose the skill into smaller parts (Davids et al., 2001; Ford et al., 2010; Reid et al., 2010). In swimming, coaches typically "break the stroke down" or decompose the stroke into smaller components when working on skill development (Brackley, Barris, et al., 2020; Junggren et al., 2018). Such pedagogical approaches are based on the assumption that each skill component of the stroke must be independently mastered before re-integrated into the full stroke movement (Dicks et al., 2008; Whelan et al., 2016). For instance, the full freestyle stroke is reduced to the *Long Dog* drill, whereby the above-water recovery phase is removed, in order to focus on the underwater phases of the stroke. The efficacy of such part-whole practice tasks continues to receive criticism as whole training approaches have been suggested to better facilitate skill learning for continuous and repetitive tasks, such as swimming (F. E. Fontana et al., 2009). Further, there is a debate within the contemporary skill acquisition literature as to whether the skills acquired during task decomposition practice approaches are either functional for, or representative of, the movement responses intended to be improved for competition performance (Barris, Farrow, et al., 2013; Pinder, Davids, et al., 2011b; Seifert et al., 2013). Consequently, there is a need to examine the efficacy of current swimming practice approaches that decomposes the skill into smaller constituent parts.

One component of freestyle swimming research that has been compared to drill swimming are upper-limb mechanics. Specifically, how movement solutions vary between the full freestyle stroke and single-arm drill swimming (Arellano et al., 2010; López et al., 2002). For example, using a three-camera setup, López et al. (2002) assessed hand displacements and velocities during different freestyle breathing patterns and one-arm freestyle drill variations. This study reported that in a single-arm drill, smaller average hand depth and lower hand velocities occurred within the propulsive phase of the stroke compared to freestyle (López et al., 2002). Arellano et al. (2010) also compared upper-limb movements between freestyle and the single-arm drill, including inter-cycle hip velocity. The findings showed that the single-arm freestyle drill presented significantly lower peak and mean hip velocity compared to freestyle (Arellano et al., 2010). Both studies highlighted how the single-arm drill effects the stroke depth, hand velocity and inter-cyclic hip velocity of freestyle swimming. However, key movement and performance characteristics expected to be improved by the drill has not been specifically assessed. The qualitative data reported in Study One (Chapter 3) regarding the specific practice approaches prescribed by elite Australian swimming coaches illustrated that the single-arm drill is used to help swimmers improve their freestyle breath timing and body alignment (Brackley, Barris, et al., 2020). Despite changes in stroke depth, hand velocity and inter-cyclic hip velocity due to the drill's constraints, future work is required to see if the single arm drill improves or represents breath timing and body alignment for competition. While the studies conducted by Arellano et al. (2010) and López et al. (2002) have reinforced that movement solutions vary biomechanically between drill and freestyle swimming, the key stroke characteristics expected to be improved when drill swimming have not been specifically assessed or considered from a representative learning design (RLD) perspective.

The RLD framework has been proposed for coaches, sport scientists and researchers to assess the extent to which practice and experimental tasks are representative of the information (e.g., perceptual stimuli, task constraints) encountered in the performance context (Krause, Farrow, Buszard, et al., 2019; Pinder, Davids, et al., 2011a, 2011b). To assist in the evaluation of practice task design, RLD proposes two key terms: functionality and action fidelity (Pinder, Davids, et al., 2011b; Pinder et al., 2013). Functionality refers to the degree to which a performer can regulate their decisions and movement solutions in the learning context with comparable information sources present during performance environment (Davids et al., 2013; Pinder, Davids, et al., 2011b). Action fidelity, on the other hand, refers to the correspondence between movement behaviours in a reference situation and movement behaviours in the experimental or simulated situation (Araújo et al., 2007; Pinder et al., 2013; Stoffregen et al., 2003). Action fidelity is said to be high when movement responses are the same in the simulated training tasks as in the performance environment (Davids et al., 2013). Conversely, swimming drills that demand significantly different movement coordination than swimming the full stroke in competition could be considered low in action fidelity (Araújo et al., 2007; Barris, Davids, et al., 2013).

Despite researchers identifying the benefits of designing and prescribing representative practice tasks (Barris, Farrow, et al., 2013; Krause, Farrow, Buszard, et al., 2019; Travassos et al., 2012), the representativeness of current practice tasks in swimming lacks empirical investigation from a biomechanics perspective. In order to investigate this critical issue, this study aimed to biomechanically compare the kinematics of full freestyle and drill swimming. Specifically, the *Long Dog* drill was compared to freestyle in the pull and push phases of the stroke. The *Polo* drill was compared to freestyle in the entry and catch, pull and push phases of the stroke. In Study One (Chapter 3), it was identified that elite swimming coaches in Australia mentioned using these two drills the most to improve key upper-limb parameters (Brackley, Barris, et al., 2020). A specific focus was placed on the upper-limb kinematics given the task goal of the drills and large contribution the upper-limbs provide to propulsion. Based on previous pilot investigations of the *Polo* drill (Brackley, Tor, et al., 2020), it was predicted that performance in relation to stroke length, stroke rate and stroke index and kinematic variables would differ between freestyle and drill swimming. It was also anticipated that trunk inclination would be greater as a direct consequence of having the head above-water when *Polo* drill swimming (de Jesus et al., 2012; Zamparo & Falco, 2010). Further, the changes to performance and upper-limb kinematic variables is anticipated to lead to a lower swimming efficiency. However, it was suggested that positive skill transfer may be inferred if the drill displayed a hand position, trunk alignment, body rotation or arm coordination that were functional for, or representative of, freestyle performance in competition.

5.3 Methods

The methodological procedures undertaken have been detailed in Chapter 4 (see section 4.2 – 4.7, p. 88 - 113) and are repeated here for clarity and to allow the chapter to read as a standalone article. However, the identification of the stroke cycle phases was altered for the *Long Dog* drill trials, as detailed in section 5.3.3, p. 129.

5.3.1 Participants

Six elite freestyle swimmers (4 male, 2 female, age 19.67 ± 2.75 years, Fédération Internationale de Natation (FINA) points 844 ± 59) volunteered to participate in this study. Characteristics of the freestyle participants included two sprint-distance specialists, two middle-distance specialists and two long-distance specialists. The selection criteria to participate were as follows: (i) attend national and international level competitions on a regular basis, (ii) have a minimum of two years specialised in their chosen distance as a freestyle swimmer and (iii) have no injuries nor be in the process of recovery at the time of testing. The selection of elite freestyle swimmers was based on an increased likelihood that such participants had well established freestyle stroke characteristics (McCabe & Sanders, 2012; Nikodelis et al., 2005; Pyne et al., 2004). Characteristics of the elite freestyle participants are presented in Table 5.1.

Table 5.1 Participant information and general physical characteristics.

Participant	Gender	Age (yrs.)	Height (cm)	Mass (kg)	Distance specialisation
SW1	Male	17	185.80	73.00	Sprint
SW2	Female	16	166.50	70.38	Middle
SW3	Male	19	190.90	84.00	Long*
SW4	Male	24	196.10	88.00	Sprint
SW5	Female	20	178.00	77.30	Middle
SW6	Male	22	190.00	90.10	Long

Sprint = 50 - 100m, Middle = 200 - 400m and Long ≥ 400 m
*Open water and long-distance specialist.

Ethical approval to conduct the study was sought and provided by the Victoria University Human Research Ethics Committee (see Appendix B – Participant information and consent). All participants received a full explanation of the nature of the study and (or a parent/guardian when a participant was under 18 years old) provided signed written consent prior to the testing procedures.

To enable the identification and tracking of anatomical landmarks, black markers (36 mm in diameter) were affixed on the right and left side of each participant. Through pilot investigations, black markers were found to offer the best contrast and could most easily be seen in the underwater environment. Marker sites included the tip of the third distal phalanx, styloid process of the lunar and radius, olecranon process of the ulna, greater tubercle of the humerus, greater trochanter, lateral epicondyle of the femur, lateral malleolus, fifth metatarsophalangeal joint and first interphalangeal joint.

5.3.2 Testing procedure and setup

The experimental protocol took place in a four-lane 25 m level deck, indoor pool with an average pool temperature of 26°C. After their individualised warm-up, participants performed the two freestyle drills, *Long Dog* and *Polo*, in randomised order. The testing protocol for each drill required participants to swim a total of 300 m broken into 2 x 25 m drill then 2 x 25 m laps of freestyle swimming., repeated three times. The instructions given to each participant were to perform the drill and swim trials as they would in training, beginning with a push start (McCabe et al., 2011). Unlike training, however, participants were further instructed to avoid performing the traditional tumble turn at the end of each 25 m lap. This was to eliminate any possible influence that the dive or tumble turn could have on the stroke kinematics (Takeda et al., 2009; Veiga & Roig, 2017). No additional feedback or instructions were given on their performance.

The swimmer's movements were captured in the middle of the pool within an 8.91 m^3 pre-calibrated volume (Figure 5.4). The volume was calibrated using a rectangular prism frame of the following dimensions: 6.0 m length (*x*-axis), 1.0 m width (*y*-axis) and 1.5 m height (*z*-axis). The calibration frame contained seventy black circular markers (36 mm in diameter) and was positioned to allow 0.5 m (*z*-axis) above-water and 1.0 m (*z*-axis) underwater with the *x*-axis aligned with the swimming direction (see Chapter 4, Figure 4.5 and 4.6, p. 95). The accuracy of the marker positions was validated using a seven–camera motion analysis system (T40 series, Vicon Nexus, Oxford, UK) in an indoor area. The cameras were mounted at a height of 1.5 ± 0.9 m and placed in an arc around the frame. Reflective markers were attached to the centre of each of the marker locations on the frame. The accuracy of the marker locations was 0.03 mm for *x*-, *y*- and *z*-axes, respectively.

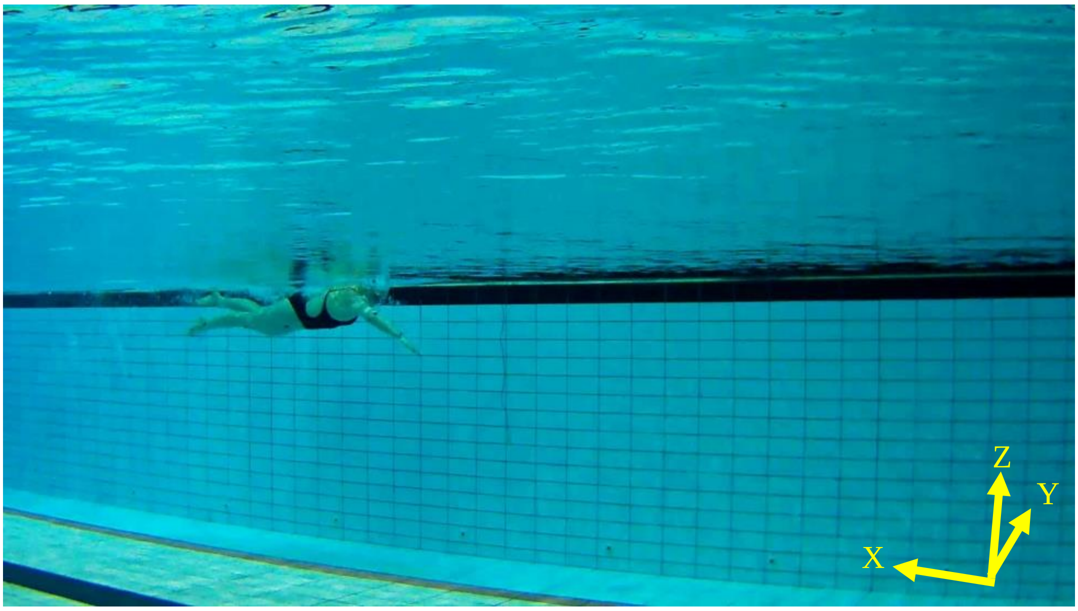


Figure 5.4 Underwater camera view of swimmer within the pre-calibrated volume.

The calibration frame and swimming movement were captured using four above- and four below-water stationary cameras (SwimPro®, NSW, Australia), operating at a sample frequency of 30 Hz. The cameras were mounted onto four separate custom-made bracket mounts enabling one camera to record above-water and one camera to record underwater. Synchronisation of the images was obtained using a pair of lights visible in the field of each camera. The position of each camera was adjusted to ensure that the field of view of each camera was approximately 8.0 m long, extending at least 1.0 m beyond each side of the 6.0 m long calibration frame on the *x*-axis (Figure 5.5). Recording a space of at least 8.0 m long ensured that no calibration points within the calibration frame were lost through the correction of the cameras' lens distortions (Beardsley et al., 1992; Remondino & Fraser, 2006; Silvatti et al., 2013; Zhang, 1998). The recorded calibration frame was digitised manually to yield separate calibration files for the above- and underwater views using a bespoke Matlab (MathWorks, Natick, MA, USA) program, Cinalysis. The Cinalysis program was designed specifically for 3D analysis in swimming and has been used in previous research (Elipot et al., 2010a; Papic et al., 2020). Root mean square

(RMS) reconstruction errors of the calibration frame validation points were as follows for the *x*, *y*, *z* axis, respectively: 4.7 mm, 3.6 mm and 4.9 mm for the above-water calibration space and 4.5 mm, 3.8 mm and 6.2 mm for the below water calibration space. For full explanation of the camera setup and calibration process, refer to Chapter 4, section 4.3.2, p. 91 and section 4.3.3, p. 97 respectively.

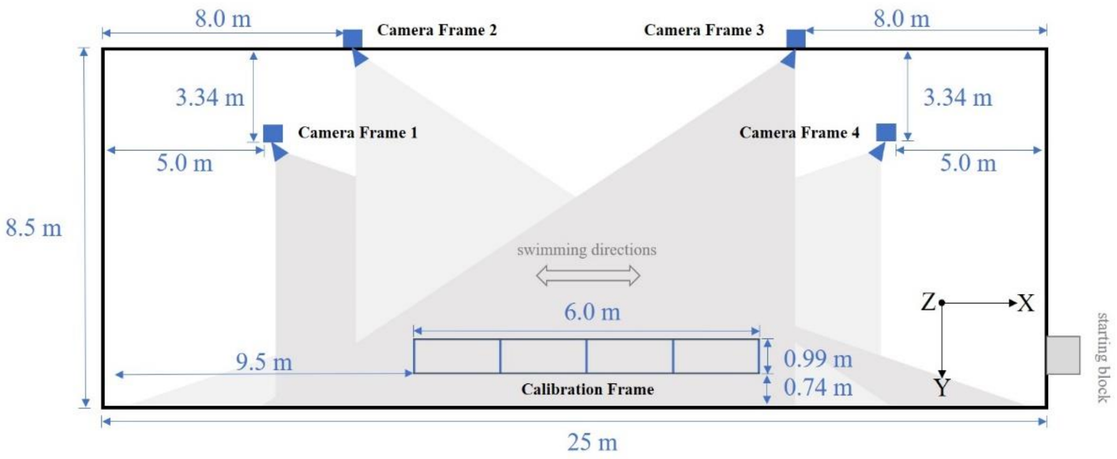


Figure 5.5 Representation of experimental setup with one camera above-water and one underwater per camera mount.

5.3.3 Data processing

The freestyle and drill swimming technique were analysed kinematically using one complete stroke cycle for each of the twelve 25 m swim laps per drill protocol and swimmer. This included six drill and six freestyle stroke cycles per drill and participant. One stroke cycle was defined as the period between the entry and re-entry of the same hand. However, as the hand did not exit the water in *Long Dog* drill swimming, one stroke cycle was defined as the period between the beginning of the pull and the consecutive pull start of the same hand for that drill. Depending on the swimming direction, either the right or left side of the swimmer was digitised. The analysed trials consisted of a combination of right- and left-handed stroke cycles both between and within participants.

The Cinalysis program was used to manually digitise the body landmarks separately for each of the eight above- and below-camera views (Elipot et al., 2010a). Even though nineteen black markers were affixed to the right and left side of each participant, the specific landmarks used for this study were limited to the tip of the third distal phalanx, styloid process of the lunar and radius, olecranon process of the ulna, greater tubercle of the humerus and the greater trochanter. Using the direct linear transformation (DLT) method (Abdel-Aziz & Karara, 1971), the digitised files where reconstructed into a single file containing the continuous 3D coordinates for each body landmark throughout the stroke cycle. The raw displacement, velocity and acceleration data were displayed in separate tabs within the file.

All data was filtered using a second-order Butterworth filter with cut-off frequencies ranging between 3 and 8 Hz (Winter, 1990). Cut-off frequencies were chosen based on residual analysis where the 3D coordinate data of each digitised landmark were filtered separately (Bartlett, 2014; Schreven et al., 2015; Winter, 2009). An example of specific cut-off frequencies determined through residual analysis for one participant trial are presented in Chapter 4, Table 4.6, p. 107. The selection of each cut-off frequency comprised of finding the breakpoints in the residual curve. A conservative approach was taken meaning that a higher cut-off frequency was selected to allow an amount of noise through the filter in order to avoid losing valuable data (Winter, 2009). Visual inspection of the data also confirmed that the smoothed data did not remove valuable maxima and minima data points. A more detailed description of the data processing techniques and methods can be found in Chapter 4, section 4.5, p. 103.

5.3.4 Data analysis

In line with previous freestyle swimming research (Chollet et al., 2000; de Jesus et al., 2012), the freestyle and drill swimming technique were divided into four separate phases: (i) entry and catch, (ii) pull, (iii) push and (iv) recovery. The description of how the phases within the stroke cycle were defined are detailed in Chapter 4, Table 4.8, p. 110. The sum of the pull and push phases was considered as the main propulsive phase of the stroke cycle, whereas the sum of the entry and catch and recovery phases was considered the main non-propulsive phase of the stroke cycle (Chollet et al., 2000; Gourgoulis et al., 2014). Further, the sum of the entry and catch, pull and push phases were defined as the underwater phase of the stroke cycle. While Koga, Homoto, Tsunokawa, and Takagi (2020) recently demonstrated that the entry and catch phase contributes to forward propulsion, this study followed the methods outlined by Chollet et al. (2000) in identifying the stroke phases.

The temporal and upper-limb parameters measured are detailed in Table 5.2. The average horizontal velocity of the hip was used to estimate the average horizontal swimming velocity (SV) during one stroke cycle (Gourgoulis, Aggeloussis, Vezos, et al., 2008; Gourgoulis et al., 2014). Evidence within the literature has confirmed that the use of the hip instead of the centre of mass to estimate SV has a tendency to either under- or overestimate velocity values (Fernandes et al., 2012; Figueiredo et al., 2009; Psycharakis & Sanders, 2009). However, the specific anatomical landmarks digitised for this study limited the centre of mass to be estimated. Consequently, when using the hip as a measure of SV and/or displacements, Fernandes et al. (2012) recommended that the hip point error magnitude needs to be taken into consideration in the interpretation of the results.

Table 5.2 Measured temporal and upper-limb displacement parameters, along with parameter definitions.

Parameter	Definition
Swimming velocity (SV) (m/s)	The average horizontal velocity of the hip during one stroke cycle.
Stroke length (SL) (m)	The horizontal displacement of the hip during a complete stroke cycle.
Stroke rate (SR) (cycles/min)	The inverse of time (minutes) to complete one stroke cycle.
Stroke index (SI) (m^2/s)	Stroke length multiplied by swimming velocity.
Upper-limb lateral motion (m)	The *y*-displacement of the finger, wrist and elbow.
Upper-limb vertical motion (m)	The *z*-displacement of the finger, wrist and elbow.

The elbow flexion/extension angle was quantified as the arc-cosine of the dot products of the upper arm (*a*) and lower arm (*b*) unit vectors (Equation 5.1) (McCabe et al., 2011; McCabe & Sanders, 2012). The elbow angle was quantified at four instances within the underwater stroke cycle: (i) hand entry, (ii) beginning of finger moving horizontally backwards, (iii) finger vertically aligned with shoulder and (iv) end of backwards movement (McCabe et al., 2011).

$$elbow\ angle = \text{acos}\left(\frac{a \cdot b}{|a||b|}\right) \qquad [\mathbf{5.1}]$$

The trunk was defined as the segment formed between the shoulder ($S_{houlder}$) and hip (H_{ip}). Therefore, to assess body alignment, the trunk inclination was calculated as the angle between the trunk and the horizontal plane and was estimated according to Equation 5.2 (Zamparo et al., 2009).

$$trunk\ inclination = arctan\frac{(S_{houlder} - H_{ip})_z}{(S_{houlder} - H_{ip})_x} \qquad [\mathbf{5.2}]$$

5.3.5 Digitising reliability

Two operators digitised the swim trials of the six participants. The operators received demonstrations and underwent training to gain familiarity and accuracy with the Cinalysis program. To assess the intra- and inter-reliability (within and between operator reliability) of the two operators' digitising technique, a single stroke cycle (randomly selected) was digitised five times for all eight camera views (Osborough et al., 2015). Digitising was conducted on separate days with no repeats of the same camera view on the same day. This ensured that reliability was not artificially improved by familiarity due to the practice effect of identifying the anatomical landmarks (Sanders, Gonjo, et al., 2015).

5.3.6 Statistical analysis

To compare differences between freestyle and drill swimming for each variable, a paired t-test was used. As there were a large number of tests, the *p*-value was initially set at a confidence level of $p < 0.05$ and then adjusted using the Bonferroni–Holm correction (Harrison et al., 2020; Holm, 1979). Previous swimming studies have also used the Bonferroni-Holm correction to control for multiple comparison tests (Issurin et al., 2014; Martens et al., 2015). The Bonferroni–Holm procedure reduces the apparent significant of effects by adjusting the rejection criteria for each test. Specifically, the *p*-values are sorted from smallest to largest. Using Equation 5.3, the *p*-value was adjusted for each test. If the *p*-value was greater or equal to the adjusted *p*-value, then the *p*-value was not significant. However, if the first *p*-value was smaller than the adjusted *p*-value, than the *p*-value was declared significant.

$$P^{B\text{-}H} = \frac{\alpha}{n} \qquad [\mathbf{5.3}]$$

Where P^{B-H} is the adjusted *p*-value using Bonferroni-Holm correction, α is the initial *p*-value and n is the number of tests remaining.

Prior to comparative analysis, the normality of each calculated variable was checked using the Shapiro-Wilk test. As some variables were not normally distributed, the paired samples Wilcoxon test was used as a non-parametric alternative of the paired t-test for the statistical treatment of those variables (Harrison et al., 2020). All processed data were analysed using R studio (R Core Team, 2016) and kinematic data reported as mean values and standard deviations.

The effect size was calculated using Cohen's *d* to describe the magnitude of difference. The interpretation of the effect size for each variable was calculated in accordance to Cohen (1988) which evaluates the magnitude of differences between two means. Specifically, Cohen's *d* expressed mean differences between two groups in standard deviation units whereby if the calculated *d* equals zero, then the mean of the difference scores is equal to zero. As *d* deviates from zero, the effect size becomes larger. Accordingly, if the absolute value of Cohen's *d* was less than 0.2 it was considered a very small effect, 0.2 to 0.3 was considered as a small effect size, 0.3 to 0.5 was moderate and greater than 0.5 was considered a large effect.

5.4 Results

5.4.1 Long Dog drill

5.4.1.1 Race parameters and stroke phase durations

Mean SV, stroke rate (SR) and stroke index (SI) showed significantly lower values when *Long Dog* drill swimming, whereas the total stroke duration displayed significantly higher values (Table 5.3). Specifically, *Long Dog* drill swimming produced a 0.14 m/s lower average SV, a 4.20 cycles/min lower average SR, a 0.31 m^2/s lower average SI and a 0.43 s higher average total stroke duration. The relative duration of the push and propulsive phase of the stroke cycle displayed significantly lower average values when performing the *Long Dog* drill. No significant differences were found between freestyle and the *Long Dog* drill in relation to the stroke length and the relative duration of the pull phase.

Table 5.3 Group-based mean temporal race performance variables and relative duration of stroke phases between freestyle and the *Long Dog* drill.

Variable	Freestyle	*Long Dog*	% Difference	P	$P^{B\text{-}H}$	*d*
Swimming velocity (m/s)	0.97 ± 0.07	0.83 ± 0.08	14.82 ± 6.88	< 0.001*	0.006	1.91
Stroke length (m)	2.19 ± 0.22	2.19 ± 0.26	0.20 ± 6.62	0.26	0.050	0.02
Stroke rate (cycles/min)	27.00 ± 0.03	22.80 ± 0.03	15.60 ± 6.56	< 0.001*	0.007	2.55
Stroke index (m^2/s)	2.14 ± 0.37	1.83 ± 0.38	14.65 ± 11.00	< 0.001*	0.008	0.83
Total duration of stroke cycle (s)	2.25 ± 0.12	2.67 ± 0.21	18.94 ± 8.30	< 0.001*	0.010	2.54
Pull (% of SC)	11.11 ± 1.68	10.83 ± 1.12	2.47 ± 13.81	0.09	0.025	0.19
Push (% of SC)	13.66 ± 1.59	11.85 ± 1.68	13.27 ± 15.70	< 0.001*	0.013	1.11
Propulsive phase (%) (pull + push)	24.77 ± 2.10	22.68 ± 2.16	8.43 ± 8.62	< 0.001*	0.017	0.98

Data expressed as mean ± standard deviation, % difference (freestyle vs. *Long Dog* drill swimming), *p*-value, Bonferroni-Holm correction *p*-value and effect size.
*indicates a significant difference between freestyle and *Long Dog* drill swimming, using Bonferroni-Holm correction.
SC denotes stroke cycle.
$P^{B\text{-}H}$ denotes Bonferroni-Holm correction *p*-value.

5.4.1.2 Finger and hip velocity

The finger and hip velocity in the pull phase showed significantly lower average values when *Long Dog* drill swimming, returning moderate and large effect sizes, respectively (Table 5.4). Specifically, in the pull phase, the *Long Dog* drill produced a 0.06 m/s slower average finger velocity and a 0.23 m/s slower average hip velocity. Similarly, in the push phase, the hip velocity was slower by an average value of 0.18 m/s and returned a large effect size. No significant differences were displayed between freestyle and *Long Dog* drill swimming in relation to the finger velocity (Figure 5.6). Further, Figure 5.7 illustrates that no significant changes were observed between freestyle and *Long Dog* drill swimming in relation to hip velocity variation.

Table 5.4 Group-based mean velocity differences of the finger and hip between freestyle and the *Long Dog* drill during each the pull and push phases of the stroke cycle.

Variable (m/s)	Freestyle	*Long Dog*	% Difference	P	$P^{B\text{-}H}$	*d*
Pull						
Finger velocity	1.26 ± 0.23	1.20 ± 0.17	5.06 ± 15.69	< 0.001*	0.013	0.32
Hip velocity	1.23 ± 0.07	1.01 ± 0.10	18.33 ± 9.02	< 0.001*	0.017	2.67
Push						
Finger velocity	1.28 ± 0.21	1.36 ± 0.44	6.54 ± 36.28	0.78	0.050	0.24
Hip velocity	1.40 ±0.09	1.22 ± 0.12	12.91 ± 9.56	< 0.001*	0.025	1.70

Data expressed as mean ± standard deviation, % difference (freestyle vs. *Long Dog* drill swimming), *p*-value, Bonferroni-Holm correction *p*-value and effect size.
*indicates a significant difference between freestyle and *Long Dog* drill swimming, using Bonferroni-Holm correction.
$P^{B\text{-}H}$ denotes Bonferroni-Holm correction *p*-value.

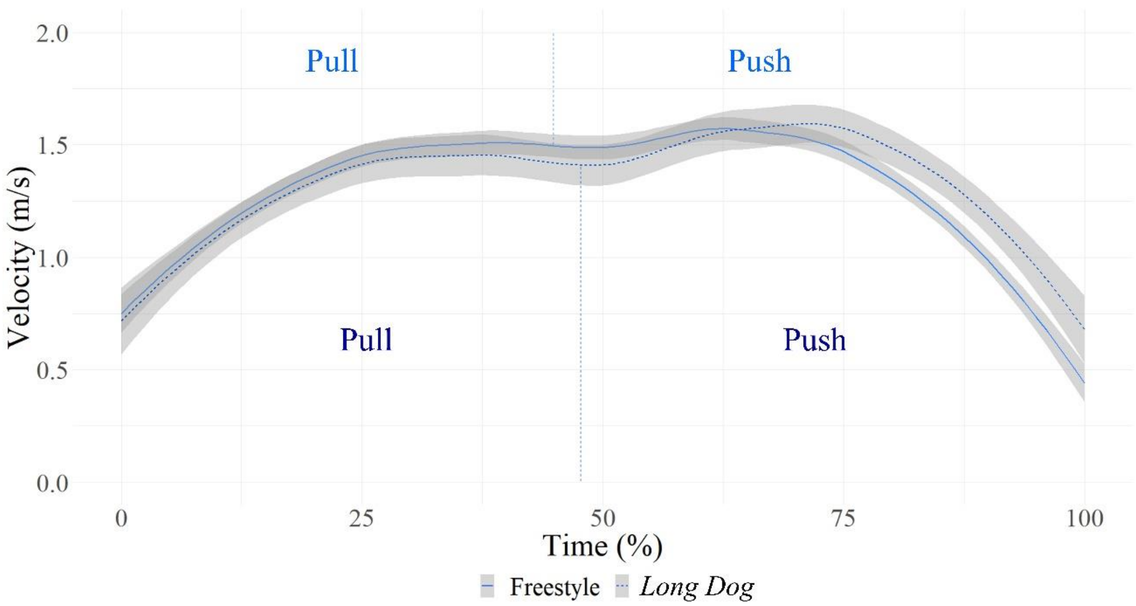


Figure 5.6 Average horizontal velocity of the finger in the pull and push phase of the stroke cycle, normalised to time with 95% confidence level around the regressed line, during freestyle and *Long Dog* drill swimming.

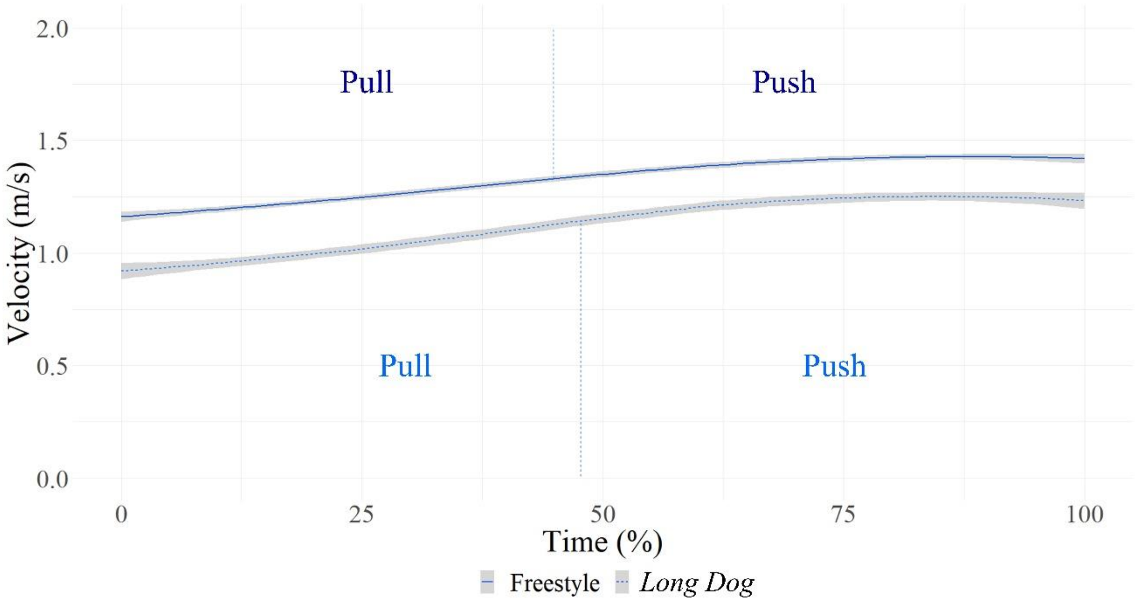


Figure 5.7 Average horizontal velocity of the hip in the pull and push phase of the stroke cycle, normalised to time with 95% confidence level around the regressed line, during freestyle and *Long Dog* drill swimming.

5.4.1.3 Upper limb displacement

In the pull phase, *Long Dog* drill swimming displayed a significantly greater finger lateral range value with a small effect size (Table 5.5 and Figure 5.8). In regards to the maximum finger vertical displacement and the lateral range of the wrist and elbow within the pull phase, no significant differences were produced between freestyle and *Long Dog* drill swimming. While the maximum vertical displacement of the finger was significantly deeper in the push phase of the stroke cycle when *Long Dog* drill swimming, the effect size was small. Further, the lateral range of the finger showed significantly greater values when performing the *Long Dog* drill and the lateral range of wrist displayed smaller values, with small effect sizes.

Table 5.5 Group-based mean lateral and vertical displacement differences of the finger, wrist and elbow between freestyle and the *Long Dog* drill in the pull and push phases of the stroke cycle.

Variable (m)	**Freestyle**	***Long Dog***	**% Difference**	**P**	**P^{B-H}**	***d***
Pull						
Max finger vertical displacement	0.76 ± 0.08	0.78 ± 0.12	2.70 ± 15.17	0.09	0.017	0.20
Finger lateral range	0.16 ± 0.08	0.18 ± 0.10	9.97 ± 35.97	0.01*	0.008	0.18
Wrist lateral range	0.13 ± 0.06	0.13 ± 0.07	2.21 ± 33.34	0.52	0.050	0.05
Elbow lateral range	0.15 ± 0.04	0.15 ± 0.05	2.24 ± 23.88	0.48	0.025	0.07
Push						
Max finger vertical displacement	0.73 ± 0.08	0.75 ± 0.12	1.71 ± 15.87	< 0.001*	0.006	0.12
Finger lateral range	0.19 ± 0.07	0.21 ± 0.06	9.39 ± 33.01	0.01*	0.010	0.26
Wrist lateral range	0.12 ± 0.08	0.10 ± 0.06	16.12 ± 37.05	< 0.001*	0.007	0.28
Elbow lateral range	0.20 ± 0.05	0.19 ± 0.04	5.97 ± 24.10	0.02	0.013	0.25

Data expressed as mean ± standard deviation, % difference (freestyle vs. *Long Dog* drill swimming), *p*-value, Bonferroni-Holm correction *p*-value and effect size.
*indicates a significant difference between freestyle and *Long Dog* drill swimming, using Bonferroni-Holm correction.
$P^{B\text{-}H}$ denotes Bonferroni-Holm correction *p*-value

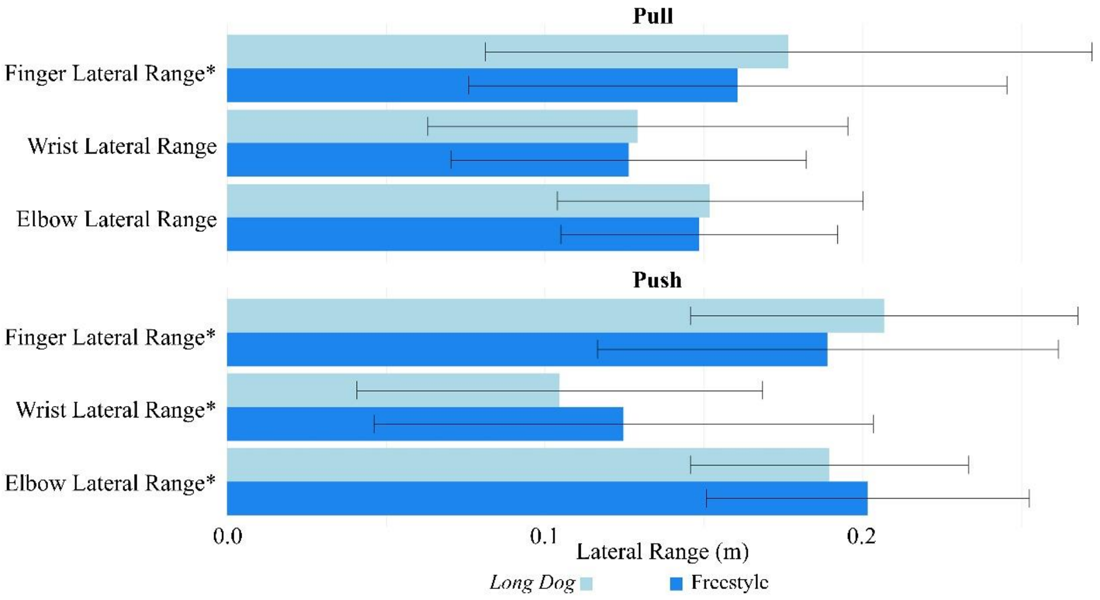


Figure 5.8 Mean magnitudes of the upper limb lateral displacement range in the pull and push phases of the stroke cycle between freestyle and *Long Dog* drill swimming. Bars represent standard deviation of the mean.

5.4.1.4 Shoulder and hip displacement

In the pull phase, the hip displayed a significantly larger average vertical range when *Long Dog* drill swimming, however the effect size was considered small (Table 5.6). Further, no significant differences were found between freestyle and *Long Dog* drill swimming in relation to the shoulder vertical range. In the push phase, the vertical range of the shoulder presented a significantly greater average value when performing the *Long Dog* drill and the effect size was large whereas the hip vertical range showed no significant differences.

Table 5.6 Group-based mean vertical displacement differences of the shoulder and hip between freestyle and the *Long Dog* drill in the pull and push phases of the stroke cycle.

Variable (m)	Freestyle	*Long Dog*	% Difference	P	$P^{B\text{-}H}$	*d*
Pull						
Shoulder vertical range	0.05 ± 0.02	0.05 ± 0.02	6.09 ± 48.20	0.23	0.050	0.15
Hip vertical range	0.12 ± 0.03	0.13 ± 0.04	8.10 ± 20.03	< 0.001*	0.013	0.28
Push						
Shoulder vertical range	0.06 ± 0.04	0.09 ± 0.05	46.24 ± 81.29	< 0.001*	0.017	0.62
Hip vertical range	0.12 ± 0.03	0.13 ± 0.03	4.55 ± 23.49	0.07	0.025	0.21

Data expressed as mean ± standard deviation, % difference (freestyle vs. *Long Dog* drill swimming), *p*-value, Bonferroni-Holm correction *p*-value and effect size.
*indicates a significant difference between freestyle and *Long Dog* drill swimming, using Bonferroni-Holm correction.
$P^{B\text{-}H}$ denotes Bonferroni-Holm correction *p*-value.

5.4.1.5 Elbow angle

When *Long Dog* drill swimming, the magnitude of the elbow flexion angle was significantly greater at the catch and shoulder instants within the stroke cycle (Table 5.7). However, despite significant differences found, the effect sizes were considered small. Figure 5.9 illustrates the small difference in elbow flexion/extension angle between freestyle and *Long Dog* drill swimming. Post hoc analysis revealed that the magnitude of the elbow angle range of motion with the pull phase was 37.6° and 42.0° for freestyle and *Long Dog* drill swimming, respectively. In the push phase, the magnitude of the elbow angle range of motion was 30.8° and 29.8° for freestyle and *Long Dog* drill swimming, respectively.

Table 5.7 Group-based mean elbow flexion/extension angle at specified instants throughout the propulsive phase of the stroke cycle between freestyle and the *Long Dog* drill.

Variable (°)	**Freestyle**	***Long Dog***	**% Difference**	**P**	**$P^{B\text{-}H}$**	***d***
Elbow angle at catch	145.1 ± 16.5	151.8 ± 18.5	4.6 ± 16.4	< 0.001*	0.017	0.38
Elbow angle at shoulder	107.6 ± 19.9	109.7 ± 20.3	2.0 ± 23.7	< 0.001*	0.025	0.11
Elbow angle at release	138.4 ± 21.5	139.6 ± 17.5	0.9 ± 19.8	0.86	0.050	0.06

Data expressed as mean ± standard deviation, % difference (freestyle vs. *Long Dog* drill swimming), *p*-value, Bonferroni-Holm correction *p*-value and effect size.
*indicates a significant difference between freestyle and *Long Dog* drill swimming, using Bonferroni-Holm correction.
$P^{B\text{-}H}$ denotes Bonferroni-Holm correction *p*-value.

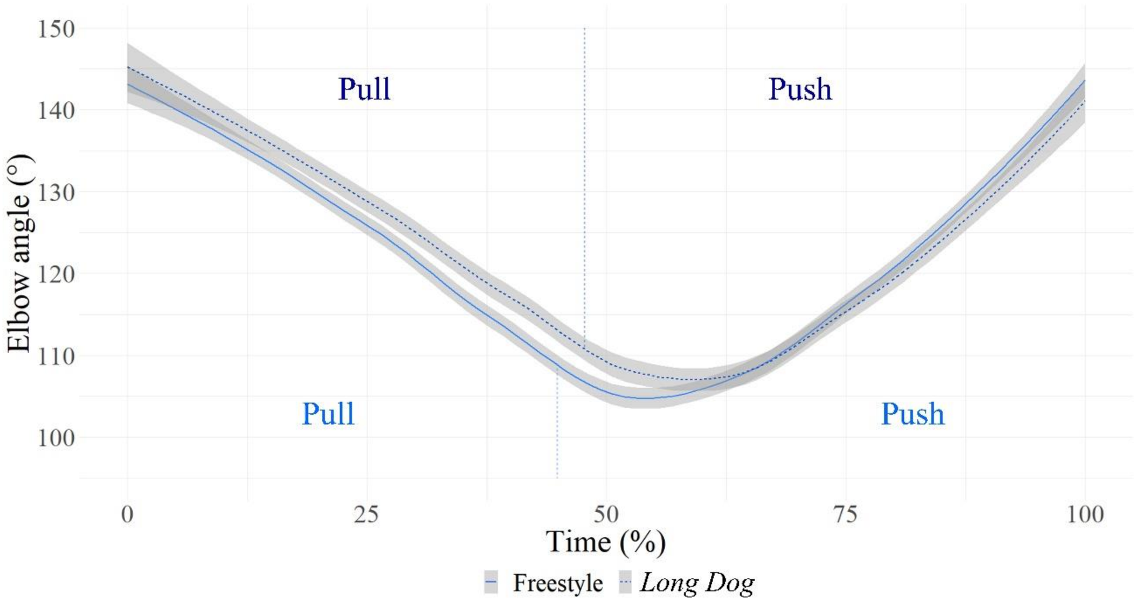


Figure 5.9 Average elbow angle in the pull and push phases of a stroke cycle, normalised to time with 95% confidence level around the regressed line, during freestyle and *Long Dog* drill swimming. Note that the lowest value on the vertical axis was increased to 70° to provide better resolution for the comparison.

5.4.1.6 Trunk inclination

The mean trunk inclination within the push phase of the stroke cycle displayed a significantly greater trunk inclination when performing the *Long Dog* drill compared to freestyle and the effect size was moderate (Table 5.8). No significant differences in mean trunk inclination were produced between freestyle and *Long Dog* drill swimming in the pull phase of the stroke cycle. Consequently, Figure 5.10 illustrates the small difference in trunk inclination between freestyle and the *Long Dog* drill.

Table 5.8 Group-based mean trunk inclination differences between freestyle and the *Long Dog* drill in the pull and push phases of the stroke cycle.

Variable (°)	Freestyle	*Long Dog*	% Difference	P	P^{B-H}	*d*
Pull						
Trunk inclination	9.83 ± 5.08	9.67 ± 4.37	1.63 ± 26.03	0.85	0.050	0.03
Push						
Trunk inclination	13.81 ± 3.87	12.69 ± 3.41	8.11 ± 20.95	< 0.001*	0.025	0.31

Data expressed as mean ± standard deviation, % difference (freestyle vs. *Long Dog* drill swimming), *p*-value, Bonferroni-Holm correction *p*-value and effect size.
*indicates a significant difference between freestyle and *Long Dog* drill swimming, using Bonferroni-Holm correction.
P^{B-H} denotes Bonferroni-Holm correction *p*-value.

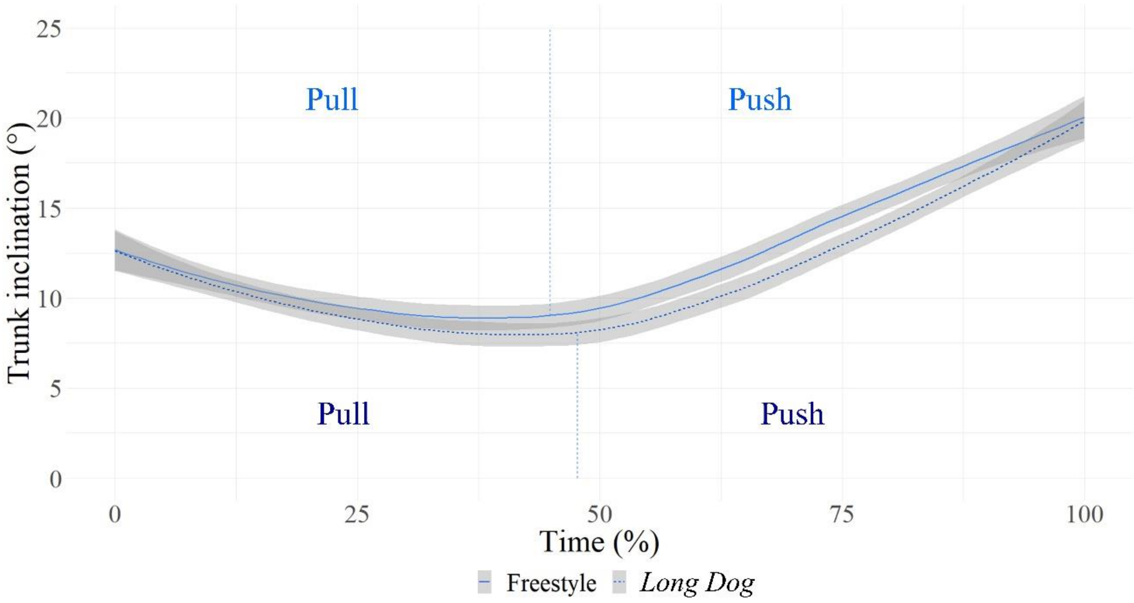


Figure 5.10 Average trunk inclination in the pull and push phases of a stroke cycle, normalised to time with 95% confidence level or regression around the regressed line, during freestyle and *Long Dog* drill swimming.

5.4.2 *Polo drill*

5.4.2.1 *Race parameters and stroke phase durations*

Mean SV, stroke length (SL), SI and total stroke duration showed significantly lower values during *Polo* drill swimming; while the SR displayed significantly higher values (Table 5.9). Specifically, *Polo* drill swimming produced a 0.09 m/s lower average SV, a 0.59 m lower average SL, a 9.00 cycles/min higher average SR, a 0.68 m^2/s lower average SI and a 0.45 s lower average stroke duration compared to freestyle swimming.

Table 5.9 Group-based mean temporal race performance variables and relative duration of stroke phases between freestyle and the *Polo* drill.

Variable	Freestyle	*Polo*	% Difference	P	P^{B-H}	*d*
Swimming velocity (m/s)	0.93 ± 0.09	0.84 ± 0.13	9.32 ± 15.57	< 0.001*	0.005	0.77
Stroke length (m)	1.97 ± 0.36	1.38 ± 0.30	30.01 ± 22.42	< 0.001*	0.005	1.79
Stroke rate (cycles/min)	28.80 ± 0.07	37.80 ± 0.15	31.44 ± 33.10	< 0.001*	0.006	1.27
Stroke index (m^2/s)	1.85 ± 0.47	1.18 ± 0.36	36.55 ± 30.31	< 0.001*	0.006	1.63
Total duration of SC (s)	2.12 ± 0.25	1.66 ± 0.26	21.39 ± 15.32	< 0.001*	0.007	1.76
Entry and catch (% of SC)	44.13 ± 9.49	33.69 ±11.59	23.68 ± 28.45	< 0.001*	0.008	0.99
Pull (% of SC)	13.79 ± 2.18	16.87 ± 4.23	22.37 ± 33.18	< 0.001*	0.010	0.92
Push (% of SC)	13.73 ± 3.21	14.93 ± 3.30	8.78 ± 34.42	0.020*	0.050	0.37
Recovery (% of SC)	28.35 ± 6.92	34.51 ± 9.06	21.71 ± 33.02	< 0.001*	0.013	0.76
Propulsive phase (%) (pull + push)	27.51 ± 4.65	31.80 ± 5.38	15.60 ± 24.66	< 0.001*	0.017	0.85
Non-propulsive phases (%) (recovery + entry and catch)	72.49 ± 4.65	68.20 ± 5.38	5.92 ± 9.36	< 0.001*	0.025	0.85

Data expressed as mean ± standard deviation, % difference (freestyle vs. *Polo* drill swimming), *p*-value Bonferroni-Holm correction *p*-value and effect size.
*indicates a significant difference between freestyle and *Polo* drill swimming, using Bonferroni-Holm correction.
SC denotes stroke cycle.
P^{B-H} denotes Bonferroni-Holm correction *p*-value.

The stroke phase durations differed significantly between freestyle and *Polo* drill swimming (Figure 5.11). Notably, the entry and catch stroke phase showed a significantly lower relative duration when performing the *Polo* drill, while during the pull, push and recovery phases of the stroke cycle, the *Polo* drill was significantly higher in relative stroke durations.

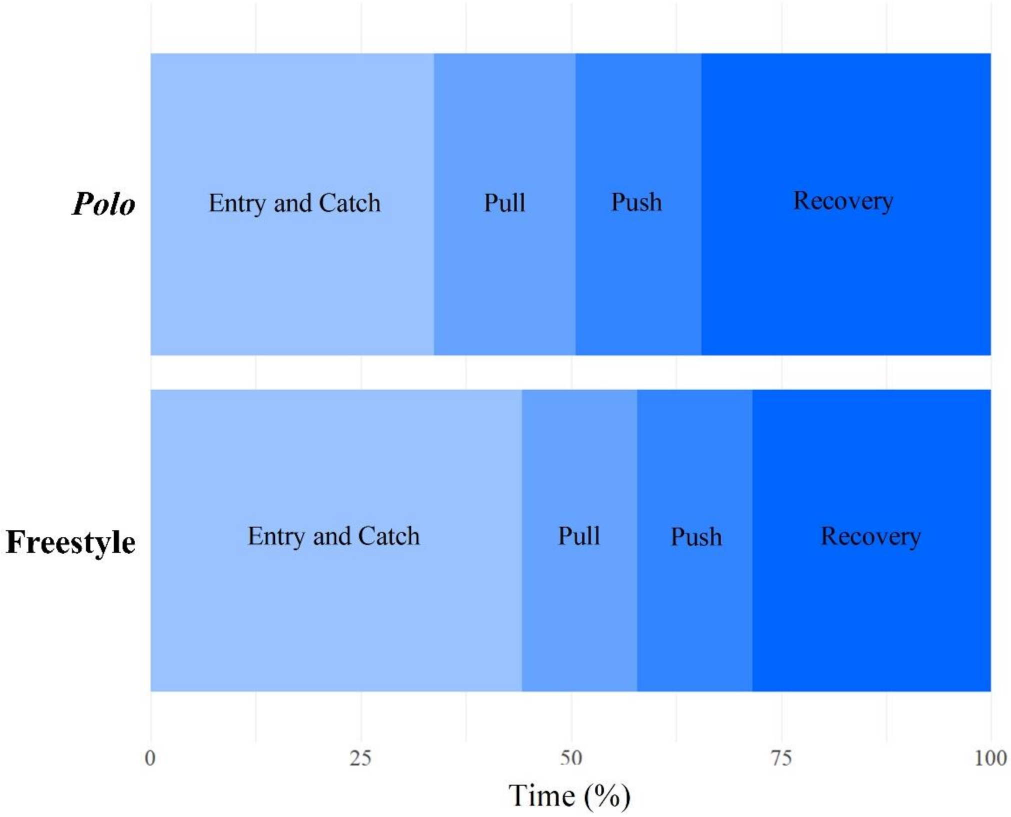


Figure 5.11 Comparison of mean stroke phase durations, expressed as a percentage of the stroke cycle, between freestyle and *Polo* drill swimming.

5.4.2.2 Finger and hip velocity

From a group-based analysis perspective, the mean horizontal velocity of the hip did not display significant differences between freestyle and *Polo* drill swimming during the entry and catch phase of the stroke cycle (Table 5.10). Conversely, the mean horizontal velocity of the finger showed significantly lower values in the entry and catch phase of the stroke cycle by 0.26 m/s when performing the *Polo* drill (Figure 5.12). Within the pull and push phases of the stroke cycle, the horizontal velocity of the finger presented significantly higher values when *Polo* drill swimming. However, the horizontal velocity of the hip displayed no significant differences within the pull phase of the stroke cycle (Figure 5.13). In contrast, horizontal velocity of the hip was significantly lower within the push phase of the stroke cycle.

Table 5.10 Group-based mean velocity differences of the finger and hip between freestyle and *Polo* drill swimming during each of the underwater stroke cycle phases.

Variable (m/s)	Freestyle	*Polo*	% Difference	P	$P^{B\text{-}H}$	*d*
Entry and Catch						
Finger velocity	1.33 ± 0.21	1.07 ± 0.28	19.33 ± 25.42	< 0.001*	0.008	1.04
Hip velocity	1.27 ±0.07	1.27 ± 0.11	0.25 ± 6.90	0.73	0.050	0.03
Pull						
Finger velocity	1.10 ± 0.18	1.32 ± 0.22	20.94 ± 18.52	< 0.001*	0.010	1.13
Hip velocity	1.22 ± 0.08	1.22 ± 0.14	0.68 ± 8.93	0.31	0.025	0.80
Push						
Finger velocity	1.33 ± 0.25	1.68 ± 0.27	26.37 ± 23.67	< 0.001*	0.013	1.34
Hip velocity	1.40 ± 0.19	1.31 ± 0.12	5.85 ± 13.41	< 0.001*	0.017	0.50

Data expressed as mean ± standard deviation, % difference (freestyle vs. *Polo* drill swimming), *p*-value, Bonferroni-Holm correction *p*-value and effect size.
*indicates a significant difference between freestyle and *Polo* drill swimming, using Bonferroni-Holm correction.
$P^{B\text{-}H}$ denotes Bonferroni-Holm correction *p*-value.

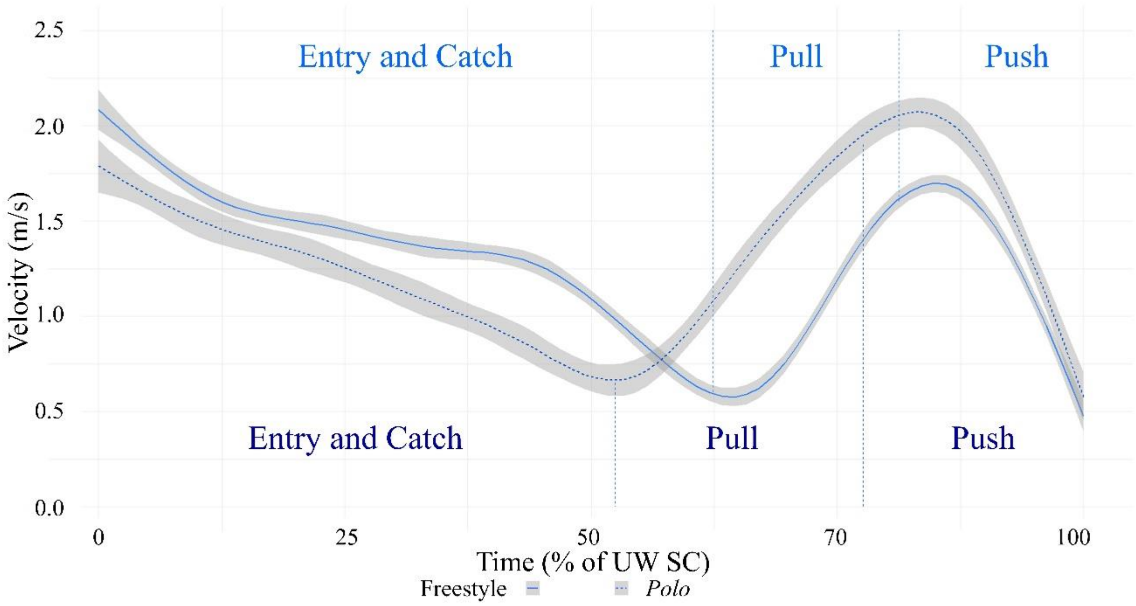


Figure 5.12 Smoothed average horizontal velocity curve of the finger in the underwater phase of the stroke cycle, normalised to time with 95% confidence level or regression around the regressed line, during freestyle and *Polo* drill performance.

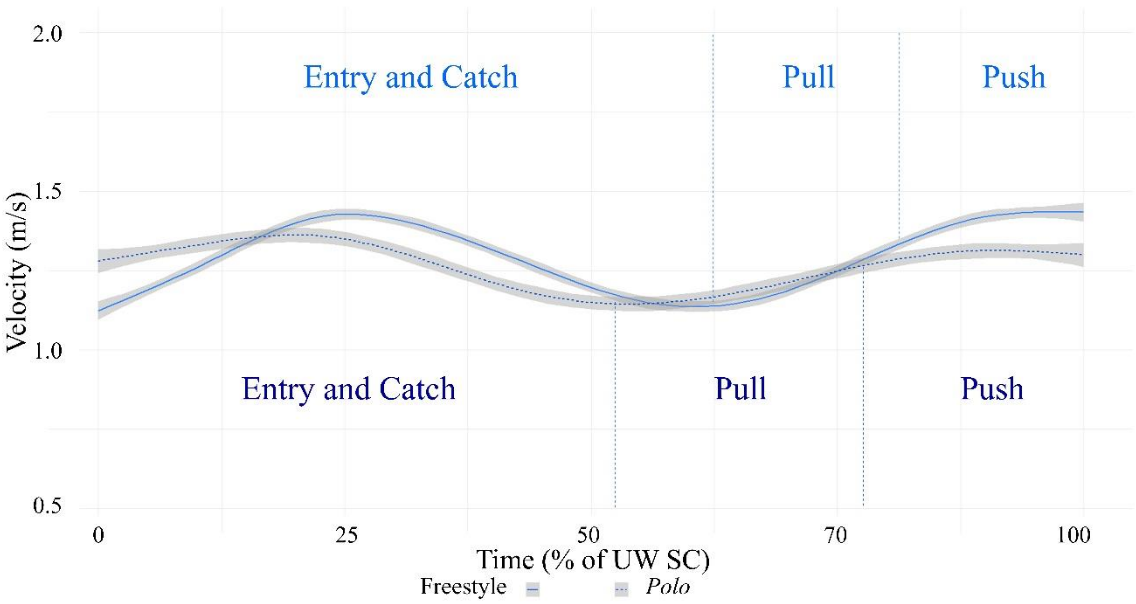


Figure 5.13 Average horizontal velocity of the hip in the underwater phase of the stroke cycle, normalised to time with 95% confidence level or regression around the regressed line, during freestyle and *Polo* drill swimming.

5.4.2.3 Upper limb displacement

Throughout the underwater phase of the stroke cycle, the maximum vertical displacement of the finger displayed significantly lower average values when performing the *Polo* drill and returned large effect sizes (Table 5.11). Within the entry and catch phase of the stroke cycle, the lateral displacement range of the finger and wrist were not significantly different between freestyle and *Polo* drill swimming (Figure 5.14). The elbow lateral range showed a significantly higher average value when *Polo* drill swimming during the entry and catch phase, with significantly lower ranges in the pull and push phases of the stroke cycle. *Polo* drill swimming produced a significantly greater finger lateral range in both the pull and push phases of the stroke cycle, whereas the lateral range of the wrist showed a significantly lower value in the pull phase compared to freestyle. No significant differences were found between freestyle and *Polo* drill swimming in relation to the lateral range of the wrist within the push phase of the stroke cycle.

Table 5.11 Group-based mean lateral and vertical displacement differences of the finger, wrist and elbow between freestyle and the *Polo* drill in the underwater phases of the stroke cycle.

Variable (m)	Freestyle	*Polo*	% Difference	P	P^{B-H}	*d*
Entry and Catch						
Max finger vertical displacement	0.49 ± 0.07	0.43 ± 0.10	13.15 ± 21.12	< 0.001*	0.004	0.77
Finger lateral range	0.17 ± 0.07	0.16 ± 0.08	3.85 ± 47.28	0.45	0.017	0.08
Wrist lateral range	0.15 ± 0.07	0.15 ± 0.07	0.39 ± 59.36	0.95	0.050	0.01
Elbow lateral range	0.11 ± 0.04	0.13 ± 0.05	19.80 ± 49.03	< 0.001*	0.005	0.51
Pull						
Max finger vertical displacement	0.73 ± 0.06	0.64 ± 0.09	12.01 ± 10.17	< 0.001*	0.005	1.16
Finger lateral range	0.15 ± 0.09	0.17 ± 0.07	13.11 ± 48.25	< 0.001*	0.006	0.25
Wrist lateral range	0.11 ± 0.06	0.09 ± 0.04	19.34 ± 46.46	< 0.001*	0.006	0.44
Elbow lateral range	0.15 ± 0.04	0.09 ± 0.05	43.69 ± 30.43	< 0.001*	0.007	1.48
Push						
Max finger vertical displacement	0.70 ± 0.07	0.62 ±0.10	11.79 ± 14.00	< 0.001*	0.008	0.95
Finger lateral range	0.16 ± 0.09	0.19 ± 0.08	17.42 ± 63.98	< 0.001*	0.010	0.35
Wrist lateral range	0.11 ± 0.09	0.10 ± 0.07	7.35 ± 108.85	0.64	0.025	0.10
Elbow lateral range	0.19 ± 0.08	0.14 ± 0.07	25.44 ± 44.14	< 0.001*	0.013	0.65

Data expressed as mean ± standard deviation, % difference (freestyle vs. *Polo* drill swimming), *p*-value, Bonferroni-Holm correction *p*-value and effect size.
*indicates a significant difference between freestyle and *Polo* drill swimming, using Bonferroni-Holm correction.
P^{B-H} denotes Bonferroni-Holm correction *p*-value.

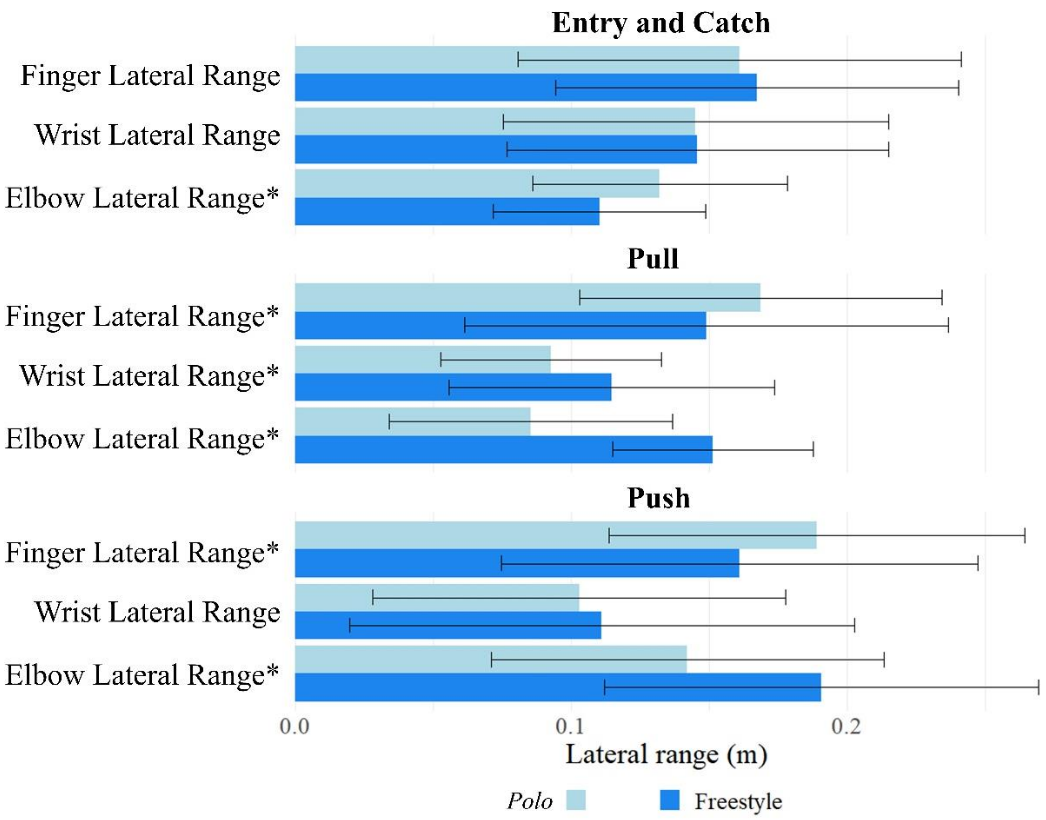


Figure 5.14 Mean magnitudes of the upper limb lateral displacement range in the entry and catch, pull and push phases of the stroke cycle between freestyle and the *Polo* drill for group of participants. Bars represent standard deviation of the mean.

5.4.2.4 Shoulder and hip displacement

The mean vertical displacement range of the shoulder and hip during the underwater phase of the stroke cycle were significantly different between freestyle and *Polo* drill swimming (Table 5.12). Notably, *Polo* drill swimming showed smaller shoulder and hip vertical range values by 0.04 m and 0.07 m, respectively. Looking at the separate phases of the underwater stroke cycle, the vertical range of the shoulder within the entry and catch and pull phases were significantly different between freestyle and *Polo* drill swimming but not within the push phase. The maximum vertical displacement of the shoulder during the entire underwater phase of the stroke cycle was significantly shallower by 0.05 m during *Polo* drill swimming. However, no significant differences were evident in the maximum vertical displacement of the hip.

Table 5.12 Group-based mean vertical displacement differences of the shoulder and hip between freestyle and the *Polo* drill in the underwater phase of the stroke cycle.

Variable (m)	Freestyle	*Polo*	% Difference	P	$P^{B\text{-}H}$	*d*
Entry and Catch						
Shoulder vertical range	0.08 ± 0.04	0.04 ± 0.03	51.56 ± 51.82	< 0.001*	0.005	1.14
Hip vertical range	0.22 ± 0.08	0.12 ± 0.07	45.40 ± 41.37	< 0.001*	0.006	1.35
Pull						
Shoulder vertical range	0.06 ± 0.02	0.04 ± 0.02	41.86 ± 43.40	< 0.001*	0.006	1.22
Hip vertical range	0.13 ± 0.03	0.10 ± 0.03	26.33 ± 27.97	< 0.001*	0.007	1.06
Push						
Shoulder vertical range	0.05 ± 0.03	0.06 ± 0.03	-2.20 ± 92.95	0.83	0.050	0.03
Hip vertical range	0.12 ± 0.03	0.09 ± 0.03	18.33 ± 32.27	< 0.001*	0.008	0.74
Mean						
Shoulder vertical range	0.15 ± 0.04	0.11 ± 0.03	29.14 ± 27.20	< 0.001*	0.010	1.33
Hip vertical range	0.27 ± 0.02	0.20 ± 0.04	25.40 ± 13.89	< 0.001*	0.013	2.15
Max shoulder vertical displacement	0.16 ± 0.03	0.11 ± 0.03	29.30 ± 18.98	< 0.001*	0.017	1.51
Max hip vertical displacement	0.37 ± 0.02	0.37 ± 0.03	1.26 ± 7.87	0.14	0.025	0.19

Data expressed as mean ± standard deviation, % difference (freestyle vs. Polo drill swimming), *p*-value, Bonferroni-Holm correction p-value and effect size.
*indicates a significant difference between freestyle and Polo drill swimming, using Bonferroni-Holm correction.
$P^{B\text{-}H}$ denotes Bonferroni-Holm correction *p*-value.

5.4.2.5 Elbow angle

The mean elbow flexion/extension angle throughout the underwater phase of the stroke cycle between freestyle and *Polo* drill swimming is presented in Figure 5.15. At the entry and catch instants throughout the stroke cycle, the mean magnitude of elbow flexion/extension angle was significantly different between freestyle and *Polo* drill swimming (Table 5.13). Specifically, *Polo* drill swimming presented a larger elbow extension angle at hand entry by 20.29° and a smaller elbow flexion angle at hand catch by 7.25°. No significant differences were found between freestyle and *Polo* drill swimming at the shoulder and release instants. Post hoc analysis revealed that the magnitude of the elbow angle range of motion within the pull phase was 41.93° and 32.87° for freestyle and *Polo* drill swimming, respectively. Further, the magnitude of the elbow angle range of motion within the push phase was 23.92° and 25.09° for freestyle and *Polo* drill swimming, respectively.

Table 5.13 Group-based mean elbow flexion/extension angle at specified instants throughout the underwater phase of the stroke cycle between freestyle and the *Polo* drill.

Variable (°)	Freestyle	*Polo*	% Difference	P	P^{B-H}	*d*
Elbow angle at entry	120.4 ± 33.2	140.7 ± 30.6	16.9 ± 35.1	< 0.001*	0.013	0.64
Elbow angle at catch	150.7 ± 10.3	143.5 ± 18.4	4.81 ± 15.3	< 0.001*	0.017	0.49
Elbow angle at shoulder	108.8 ± 10.5	110.6 ±18.5	1.67 ± 19.1	0.04	0.025	0.12
Elbow angle at release	132.7 ± 19.6	135.7 ± 16.7	2.25 ± 17.0	0.39	0.050	0.16

Data expressed as mean ± standard deviation, % difference (freestyle vs. *Polo* drill swimming), *p*-value, Bonferroni-Holm correction *p*-value and effect size.
*indicates a significant difference between freestyle and *Polo* drill swimming, using Bonferroni-Holm correction.
P^{B-H} denotes Bonferroni-Holm correction *p*-value.

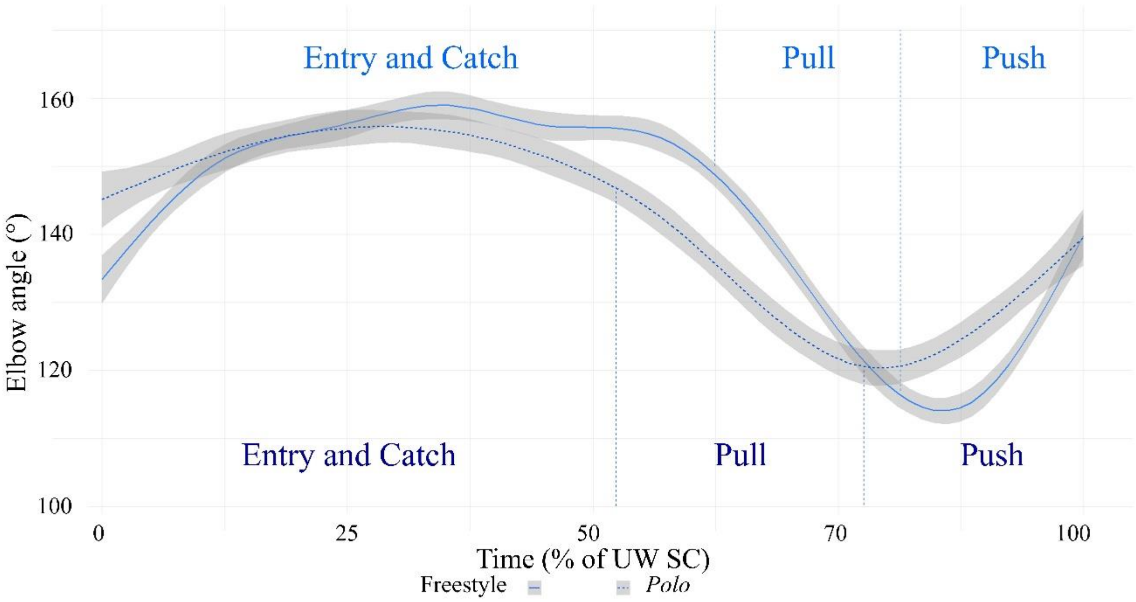


Figure 5.15 Smoothed average elbow angle in the underwater phase of a stroke cycle, normalised to time with 95% confidence level or regression around the regressed line, during freestyle and *Polo* drill swimming. Note that the lowest value on the vertical axis was increased to 100° to provide better resolution for the comparison.

5.4.2.6 Trunk inclination

The mean trunk inclination for the whole underwater phase of the stroke cycle revealed a significantly greater angle by 6.69° when *Polo* drill swimming and returned a large effect size (Table 5.14). Freestyle swimming presented the highest average value for trunk inclination throughout the entry and catch phase of the stroke cycle during freestyle; whereas *Polo* drill swimming presented the highest trunk inclination value during the push phase of the stroke cycle (Figure 5.16). The pull phase of the stroke cycle displayed the lowest trunk inclination value during both freestyle and *Polo* drill swimming.

Table 5.14 Group-based mean trunk inclination differences between freestyle and the *Polo* drill in the underwater phases of the stroke cycle.

Variable (°)	**Freestyle**	***Polo***	**% Difference**	**P**	**P^{B-H}**	***d***
Entry and Catch						
Trunk inclination	18.75 ± 5.32	23.44 ± 3.90	25.00 ± 27.88	< 0.001*	0.013	1.00
Pull						
Trunk inclination	13.80 ± 5.56	22.11 ± 4.19	60.19 ± 38.36	< 0.001*	0.017	1.69
Push						
Trunk inclination	16.24 ± 6.08	26.33 ± 5.63	63.98 ± 41.81	< 0.001*	0.025	1.77
Mean						
Trunk inclination	17.38 ± 4.68	24.08 ± 3.54	38.50 ± 26.44	< 0.001*	0.050	1.61

Data expressed as mean ± standard deviation, % difference (freestyle vs. *Polo* drill swimming), *p*-value, Bonferroni-Holm correction *p*-value and effect size.
*indicates a significant difference between freestyle and *Polo* drill swimming, using Bonferroni-Holm correction.
P^{B-H} denotes Bonferroni-Holm correction *p*-value.

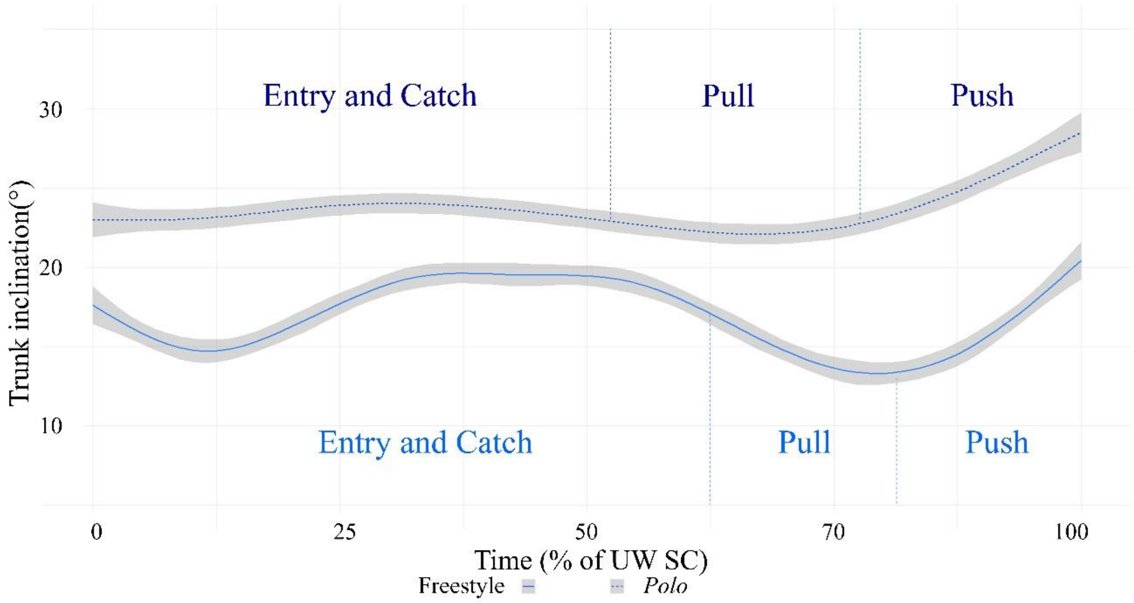


Figure 5.16 Average trunk inclination in the underwater phase of a stroke cycle, normalised to time with 95% confidence level or regression around the regressed line, during freestyle and *Polo* drill swimming.

5.5 Discussion

The primary aim of this study was to compare upper-limb and trunk kinematics of full freestyle and drill swimming. The *Long Dog* and *Polo* drill were selected as the vehicle for this assessment as they have been identified as two of the most commonly prescribed freestyle drills by elite Australian swimming coaches (see Chapter 3) (Brackley, Barris, et al., 2020). Swimming coaches prescribed the *Long Dog* drill to improve or condition body rotation, trunk alignment and the hand path within the pull phase of the freestyle stroke. The *Polo* drill was prescribed to improve the hand position and arm coordination within the entry and catch and pull phases of the stroke (Brackley, Barris, et al., 2020; Lucero, 2015). Currently, there is no empirical evidence to support that the temporal and kinematic parameters expected to be improved through the particular drills represent the full freestyle stroke. Race parameters, stroke phase durations, upper-limb kinematics and the trunk inclination were assessed using 3D video-based kinematic analysis. The trunk inclination was measured to assess trunk alignment. Further, the vertical range of the shoulder and hip were measured as alternative indicators of body rotation. Previous studies have investigated the effect the single-arm freestyle drill has on hip velocity, breathing pattern and body roll (Arellano et al., 2010; López et al., 2002). However, this study is the first to assess the specific kinematic parameters expected to be improved by specific drill-based tasks.

5.5.1 Long Dog drill

The *Long Dog* drill produced a significantly slower swimming velocity (SV) accompanied by significantly lower average stroke index (SI) value. The SI value was influenced by the significantly lower average SV value as stroke length (SL) was not modified significantly between freestyle and the *Long Dog* drill. Studies have suggested that lower SV, SI and finger velocity values within the pull phase of the stroke cycle may indicate an overall lower swimming efficiency (Barbosa et al., 2010; Seifert, Toussaint, Alberty, Schnitzler, & Chollet, 2010). Further, the total stroke duration was shorter when *Long Dog* drill swimming. Within the total stroke duration, the relative duration of the pull phase displayed no significant difference between freestyle and *Long Dog* drill swimming whereas the push phase was significantly shorter. Consequently, the propulsive phase of the stroke was significantly shorter when *Long Dog* drill swimming. Despite these temporal alterations to the stroke, the hand path trajectory and trunk inclination were not significantly different between freestyle and *Long Dog* drill swimming. This demonstrates that *Long Dog* drill swimming represents some key freestyle performance parameters. However, a consequence associated with the *Long Dog* drill is that the shoulder displayed a significantly larger vertical range of motion within the push phase of the stroke. Yanai (2003) has suggested that a larger shoulder roll may disrupt the streamlined body position, increasing resistive forces and reducing the efficiency of propulsive forces. The findings reinforce what swimming coaches understand in regards to the negative consequences associated with drill prescription, as described by one of the interviewed coaches in Study One (Chapter 3):

> I would say, and this is the problem with any drills that if you're using it to focus on a specific aspect, nine times out of ten it's going to negatively affect at least one other part of the stroke. So, whenever you use a drill you've got to understand is… so you've got to be very mindful of the affect. (SC4)

However, the significantly slower SV when performing the *Long Dog* drill did not reflect the coaches' perspective in regards to performing drills at race specific speeds (see Chapter 3, section 3.4.1.3, p. 72). Consequently, it is recommended that coaches closely assess if the *Long Dog* drill improves and represents the swimmer's body rotation, trunk inclination and upper-limb kinematics for competition performance. Further, the speed in which drills are performed may differ depending on the skill level of the athlete and if the drill is prescribed to either improve or reinforce a particular skill.

5.5.1.1 Pull phase

In the pull phase of the stroke, the upper-limb kinematics were not altered significantly when performing the *Long Dog* drill. This suggests that there was no difference in participant's hand positioning and depth compared to freestyle. However, there was significantly less elbow flexion at the catch and shoulder instants when *Long Dog* drill swimming. The magnitude of the elbow angle has been associated with the hand path trajectory, force production and upper-limb velocity (Maglischo, 2003). Consequently, the slightly larger finger lateral range of motion and moderately slower finger velocity when performing the *Long Dog* drill may have altered the magnitude of the elbow angle. Seifert, Toussaint, et al. (2010) proposed that a lower elbow position throughout the propulsive phase of the stroke could reduce the propulsive surface of the upper limbs, resulting in a lower hand (finger) velocity. Alternatively, it is possible that the slower finger velocity is a consequence of swimmers explicitly focusing on the hand path in order to avoid the hand slipping backwards through the water. Seifert et al. (2014) described slippage through the water as when the hand speed remains high when moving through the water yet force generation is low or not well orientated to catch any water and overcome drag. Despite the slower swimming and finger velocity in the pull phase, the relative pull phase duration showed no significant difference between freestyle and the *Long Dog* drill. It is suggested that swimmers were able to catch the water without the hand slipping backwards given the lower SR, large elbow angle range of motion with the pull phase and unaltered SL when *Long Dog* drill swimming (McCabe et al., 2011; Seifert, Chollet, et al., 2004; Vorontsov & Rumyantsev, 2000).

Examination of the shoulder movement and trunk inclination within the push phase displayed that performing the *Long Dog* drill produced no significant changes to the shoulder vertical range of motion and streamlined body position. However, the hip velocity was significantly lower and the vertical range of the hip showed a slightly larger range of motion, yet the effect size was small. Despite the lower hip velocity, the findings suggest that the leg kick frequency when *Long Dog* drill swimming continued to support the recommended streamlined body position within the pull phase of the freestyle stroke cycle (Gourgoulis et al., 2014). Therefore, the findings from the group analysis suggests that swimmers may have utilised a similar body rotation, trunk inclination and trajectory of the upper limbs within the pull phase for the freestyle and *Long Dog* drill swimming trials. The vertical range of the shoulder and hip were measured as an alternative indicator of body rotation as the current experimental setup and pool did not enable body roll to be measured. To draw more accurate conclusions on the effect *Long Dog* drill swimming has on body rotation, an experimental design that allows this parameter to be measured should be considered in a future study.

5.5.1.2 Push phase

In the push phase of the stroke cycle, the maximum finger vertical displacement and the lateral range of the finger and wrist showed significant differences between freestyle and the *Long Dog* drill, yet the effect sizes were small ($p < 0.010$, $d \leq 0.28$). Further, the lateral range of the elbow and elbow angle at the release instant displayed no significant differences. These results suggest that *Long Dog* drill swimming does not greatly alter the upper-limb motion of the freestyle stroke in the push phase.

The shoulder displayed a significantly larger vertical range of motion by 56% when *Long Dog* drill swimming whereas no significant differences were observed in the hip vertical range and hip velocity was significantly lower by 13%. The greater vertical range of the shoulder may be related to the slower SV when *Long Dog* drill swimming, causing a greater shoulder roll magnitude (Psycharakis & Sanders, 2008; Yanai, 2003). Additionally, the lack of significant difference in the hip vertical range of motion and lower hip velocity when *Long Dog* drill swimming could be associated with the lower SR (Andersen, Sinclair, McCabe, & Sanders, 2018). Studies have reported that the magnitude of the hip and shoulder roll are influenced by swimming speed, the flutter kick frequency, breathing patterns, buoyancy and fatigue (Andersen et al., 2018; McCabe, Sanders, & Psycharakis, 2015; Psycharakis & McCabe, 2011; Psycharakis & Sanders, 2008). While the recovery of the upper limbs does not affect propulsion directly, the motion of the limbs in the recovery phase can significantly impact performance by influencing body rotation (Sanders et al., 2017). Therefore, the larger shoulder vertical range of motion within the push phase is suggested to be a negative consequence associated with the *Long Dog* drill prescription.

5.5.2 Polo drill

The *Polo* drill produced a greater elbow angle extension at hand entry, a smaller medial-lateral range of the wrist within the pull phase of the stroke cycle and greater elbow flexion at the hand catch instant compared to freestyle. Despite the lower SV, it is possible that these stroke modifications are beneficial to skill learning as such movement patterns tend to be displayed at greater race-pace swimming (Guignard, Rouard, Chollet, Hart, et al., 2017; McCabe et al., 2011; Sanders et al., 2017). However, having the head above-water when performing the *Polo* drill displayed a significantly greater trunk inclination. This finding is supported by previous studies investigating head above-water freestyle in water polo players (de Jesus et al., 2012; Zamparo & Falco, 2010). Consequently, the larger frontal/cross-sectional area of the swimmer may be related to the hand following a shallower trajectory and SL displaying shorter values when performing the *Polo* drill (Naemi et al., 2010; Toussaint & Beek, 1992; Zamparo & Falco, 2010). Further, de Jesus et al. (2012) found that the greater trunk inclination during head above-water freestyle caused the legs to sink. It is possible that the leg kick frequency declined when *Polo* drill swimming which might explain the lower SV, hip velocity and hip vertical range values (Gourgoulis et al., 2014; McCabe et al., 2011; Sanders & Psycharakis, 2009).

Additionally, as the duration of the stroke cycle was shorter when *Polo* drill swimming, SR displayed higher values. This resulted in a lower SI value when *Polo* drill swimming compared to freestyle. It was expected that swimming efficiency would be lower when *Polo* drill swimming as previous research has reported that higher physiological energy expenditure is required to displace the body through the water when the swimmers' streamlined body position is disrupted (Barbosa et al., 2010; Seifert, Toussaint, et al., 2010). Despite the significant differences in upper-limb kinematics within the entry and catch and pull phase of the stroke between freestyle and *Polo* drill swimming, the movement adjustments of certain variables could suggest potential points of positive transfer between *Polo* drill swimming and race-pace freestyle.

5.5.2.1 Entry and catch phase

In the entry and catch phase, the lateral range of the finger and wrist were not significantly modified when *Polo* drill swimming. This suggested that when performing the *Polo* drill, participants were able to enter and position their hand in a similar path to freestyle. Even though the lateral range of the finger and wrist displayed no significant differences when performing the *Polo* drill, the lateral range of the elbow was larger and the average finger velocity was lower in the entry and catch phase. Sanders et al. (2019) suggested that the consistency of the hand path is a result of effective compensation through functional variability of segmental and joint contributions across other variables. Therefore, it would appear that modifications to the elbow lateral range when performing the *Polo* drill may have helped facilitate a similar lateral range of motion of the finger to freestyle.

The *Polo* drill showed a significantly larger elbow angle at the entry instant combined with a significantly less extended elbow at the catch instant. It is possible that swimmers quickly flexed their elbow to catch the water sooner in order to enable a longer propulsive phase (Lerda & Cardelli, 2003; Seifert, Chollet, et al., 2004). Sanders et al. (2017) suggested that entering the hand further in front of the head, with greater elbow extension, tends to be favoured by sprint-distance swimmers as their hand enters the propulsive phase of the stroke cycle sooner. Middle- and long-distance swimmers, however, tend to display greater elbow flexion at hand entry as they enter the hand above their head and glide it forward before commencing the downward and backward motion of the hand (Sanders et al., 2017). It would appear that the extended elbow angle at hand entry and greater elbow flexion at hand catch when *Polo* drill swimming reduced the forward glide duration, illustrated by the shorter entry and catch duration (Sanders et al., 2017). While the relative duration of the entry and catch phase was shorter when *Polo* drill swimming compared to freestyle, the recovery phase duration was longer. This suggests that *Polo* drill swimming may produce an earlier start to the pull phase, as displayed by the great elbow flexion at hand catch, and a relatively longer recovery time compared to freestyle. These observations suggest that despite the reduced swimming efficiency and greater elbow lateral range, *Polo* drill swimming may promote a similar hand entry position to freestyle. Further, the modified elbow angle at the entry and start of pull phase reflects movement characteristics to that encouraged for sprint-distance swimmers.

5.5.2.2 Pull and push phases

The lateral range of the finger was significantly greater within the pull and push phases of the stroke cycle when performing the *Polo* drill, although only with a small effect size. Contrary to the entry and catch phase, this indicated that the slight changes to the finger movement when *Polo* drill swimming did not greatly affect the freestyle hand path. Studies have suggested that a greater medial lateral displacement of the hand might be attributed to either a different amount of shoulder roll between experimental conditions or slower SV (Guignard, Rouard, Chollet, Hart, et al., 2017; Psycharakis & Sanders, 2010; Sanders et al., 2017).

Examination of the shoulder movement throughout the underwater phase of the stroke cycle revealed that *Polo* drill swimming displayed a significantly shallower maximal vertical displacement compared to freestyle. Notably, the vertical range of the shoulder was significantly smaller throughout the entry and catch and pull phases of the stroke cycle. Researchers have observed that swimmers tend to produce a higher shoulder and hip roll magnitude when rotating the head to take a breath (McCabe et al., 2015; Psycharakis & McCabe, 2011; Psycharakis & Sanders, 2010). This suggests that the removal of the breathing action when *Polo* drill swimming may have influenced a lower vertical range of the shoulder and hip compared to freestyle. Previous studies investigating freestyle stroke kinematics within a pre-calibrated volume have instructed participants to avoid taking breaths (de Jesus et al., 2016; McCabe et al., 2011). However, for this study, participants were instructed to perform freestyle as they would in training (taking breaths as required) in order to accurately see how performing the *Polo* drill influences freestyle kinematic variables. Future should examine the number of breaths and breathing side when comparing the difference between drill and freestyle swimming.

The wrist and elbow medial-lateral range showed significantly lower values within the pull phase of the stroke when *Polo* drill swimming. This straighter motion of the wrist and elbow, described as an ‘I’- shaped pull path, tends to be displayed in sprint-distance swimmers (Guignard, Rouard, Chollet, Hart, et al., 2017; Sanders et al., 2017). Middle- and long-distance swimmers typically display the ‘S’-shape pull path which produces less force but with less energy loss to the water (Sanders et al., 2017; Takagi et al., 2016). Consequently, the *Polo* drill may be more functional for sprint-distance specialists. Alternatively, the straighter pull path when *Polo* drill swimming could have been influenced by the significantly lower hip vertical range of motion and a greater finger width within the pull phase of the stroke compared to freestyle.

Finger velocity and the relative duration of the pull and push phases displayed higher values when *Polo* drill swimming compared to freestyle. However, the pull phase displayed a greater relative duration than the push phase. To balance the organisation of the phase durations, the finger velocity in the push phase was greater than the pull phase. While a higher hand velocity within the propulsive phase of the stroke relates to higher propulsive forces (Chollet et al., 2000; Lerda & Cardelli, 2003), it does not automatically ensure efficient propulsion generation as the hand may slip backwards through the water without helping catch any water (Seifert & Chollet, 2008; Seifert, Chollet, & Rouard, 2007; Seifert, Toussaint, et al., 2010). It is possible that swimmers' hand slipped through the water when performing the *Polo* drill given the lower SV and SL values, higher SR and smaller elbow angle range of motion within the pull phase (McCabe et al., 2011; Seifert, Chollet, et al., 2004; Vorontsov & Rumyantsev, 2000). Further, *Polo* drill swimming displayed a shallower hand path trajectory. This may have been produced by the greater trunk inclination (i.e., elevating the shoulder), shorter stroke duration (i.e., reducing the time to enable a deeper hand path) and / or greater elbow flexion displayed within the pull phase of the stroke. Therefore, while the straighter motion of the wrist and elbow within the pull phase may represent the hand path in sprint-distance swimmers, the shallower pull pattern and disrupted streamlined body position increases drag and subsequently hinders propulsion generation (McCabe et al., 2011; McCabe & Sanders, 2012).

5.5.2.3 Arm coordination

An examination of the hip velocity curves (Figure 5.13, p. 146) throughout the underwater phases of the stroke cycle revealed lower SV fluctuation when *Polo* drill swimming compared to freestyle. This could be the result of the greater propulsive continuity of the two arms and subsequently, it is possible that *Polo* drill swimming may lead to inter-arm coordination adaptations transferable to maximal race-pace swimming (de Jesus et al., 2012). Findings from de Jesus et al. (2012) have revealed that when polo players swam maximum bouts of both head above-water and normal freestyle, a superposition coordination mode of the arms was employed. The superposition coordination mode of the arms refers to the overlap in the propulsive phases of the two arms and has demonstrated higher propulsion generation (Chollet et al., 2000; Ribeiro et al., 2013; Seifert, Toussaint, et al., 2010). In freestyle swimming, researchers have illustrated that increasing swimming speed from slow to fast paces requires a higher SR and tends to lead to superposition inter-arm coordination adaptations (Chollet et al., 2000; Lerda & Cardelli, 2003; Seifert, Chollet, & Rouard, 2007; Seifert, Toussaint, et al., 2010). However, a higher SR and superposition coordination mode does not necessarily imply high SV (Seifert, Chollet, et al., 2004). This may be the case with *Polo* drill swimming.

Based on the insights from de Jesus et al. (2012) and Seifert, Chollet, et al. (2004), an alternative interpretation of the results could view slow-paced *Polo* drill swimming as a task constraint manipulation that leads to higher SR values and inter-arm coordination adaptations transferable to movement adjustments beneficial to maximal race-pace freestyle (Guignard, Rouard, Chollet, Hart, et al., 2017). Further, the superposition coordination mode and higher hand velocity is usually only exhibited in expert sprint-distance swimmers (Barbosa et al., 2010; Guignard, Rouard, Chollet, Hart, et al., 2017; Seifert, Chollet, & Rouard, 2007). Therefore, *Polo* drill swimming may help sub-elite or junior swimmers better coordinate arm actions at greater swimming speed. However, given the impact swimming velocity and pace has on inter-limb coordination (Guignard, Rouard, Chollet, Hart, et al., 2017; Seifert, Chollet, et al., 2004; Seifert, Chollet, & Rouard, 2007), further research is need to confirm whether *Polo* drill swimming represents the arm coordination patterns at greater swimming speed. Based on the insights from de Jesus et al. (2012) looking at polo players, it is possible that performing the

Polo drill at a higher SV may also facilitate the transfer of kinematic skills required in competition. That is, when comparing head above- and below-water freestyle in water polo players, de Jesus et al. (2012) reported no significant differences in upper-limb kinematics when swimming at maximum bouts. Future work is required to see if and how the *Polo* drill performed over a long period of time alters freestyle technique in competition performance.

5.6 Conclusion

This study investigated the effect of *Long Dog* and *Polo* drill swimming on freestyle kinematics. The parameters measured were specific to the task goals of the drills. Biomechanical analysis of the freestyle stroke has shown that the position and motion of the hand has a direct influence on the generation of propulsion, inter-limb coordination and body alignment (Maglischo, 2003; Sanders et al., 2017). Consequently, the *Long Dog* drill is prescribed to help swimmers improve or condition the body rotation, body alignment and the hand position within the pull phase of the freestyle stroke (Brackley, Barris, et al., 2020). Additionally, the *Polo* drill is prescribed to help swimmers improve or condition the hand position within the entry and catch and pull phases of the freestyle stroke (Brackley, Barris, et al., 2020; Lucero, 2015).

Contemporary theories on skill acquisition have criticised practice tasks that isolate or decompose the skill may hinder skill learning (Davids et al., 2008; Seifert & Davids, 2012). The group-based analysis showed that there were no significant differences in shoulder movement, trunk inclination and upper-limb motion in the pull phase of the stroke between freestyle and *Long Dog* drill swimming. This indicated that the *Long Dog* drill represents key performance parameters in the pull phase of the freestyle stroke. However, the lower SV, SI and finger velocity values suggested an overall lower swimming efficiency when performing the *Long Dog* drill. Further, as increased SV (from slow to maximal pace) may be associated with a reduced medial-lateral range of motion of the hand pull path (Guignard, Rouard, Chollet, Hart, et al., 2017), the hand path when swimming the slow-paced *Long Dog* drill may not be representative to race-pace freestyle in competition.

The *Polo* drill showed no significant differences in hand entry position to freestyle although modified the elbow angle at the entry and start of pull phase to movement characteristics to that encouraged for sprint-distance swimmers. In the pull phase, the *Polo* drill showed a straighter motion of the wrist and elbow. Further, the hand pull pattern showed shallower values and the streamlined body position was disrupted resulting in a greater trunk inclination. In regards to arm coordination, the results suggest that slow-paced *Polo* drill swimming could be considered a task constraint manipulation that leads to higher SR values and inter-arm coordination adaptations transferable to maximal race-pace freestyle. However, based on the insights from de Jesus et al. (2012) looking at polo players, it is possible that performing the *Polo* drill at a higher SV may better facilitate the transfer of arm coordination skills required in competition. While the *Long Dog* drill showed no significant differences in trunk inclination values to freestyle, coaches may want to closely assess if the drill improves and represents the swimmer's upper-limb kinematics for competition performance. However, the results from the *Polo* drill investigation suggest that the upper-limb kinematic changes when performing the drill may positively represent hand position recommendations for race-pace freestyle.

5.7 Contribution of chapter to the aims of the thesis

The aim of Study Two (Chapter 5) was to biomechanically compare the kinematics of full freestyle and drill swimming. The findings contributed to answering the second aim of this thesis, identifying kinematic differences between freestyle and the two commonly prescribed upper-limb drills from a group-based analysis perspective. However, in order to understand if these observed differences are consistent across individuals, an individual-based analysis was explored in Study Three (Chapter 6).

Chapter 6: The Effect of Drill Swimming on Freestyle Kinematics: Individual-based Analysis

This chapter is based on the following peer-reviewed journal article:

Brackley, V., Tor, E., Barris, S., Farrow, D. & Ball, K. (2020). Drill or swim, what should coaches prescribe? Individual-based analysis on the comparison of drill swimming on freestyle kinematics. *Currently under review*

6.1 Abstract

The effect of drill swimming on key freestyle movement and performance characteristics has been assessed from a group-based analysis perspective. While informative, the dynamical systems theory contends that individual-based analysis of kinematics is required in order to unravel the complex processes governing motor control. The aim of this study was to extend the current work of comparing the kinematics of full freestyle swimming and the two commonly prescribed upper-limb drills, *Long Dog* and *Polo*, to an individual-based analysis approach. Six elite freestyle specialists swam a total of 300 m for each drill divided into two 25 m laps of drill swimming followed by two 25 m laps of freestyle. Three-dimensional (3D) kinematic characteristics of freestyle and drill swimming were recorded using four above- and four below-water cameras. Anatomical landmarks were digitised and the direct linear transformation (DLT) algorithm was used to perform the 3D reconstruction. Average swimming velocity, stroke length, stroke frequency, stroke index, duration of stroke phases, upper-limb displacement, elbow angle, shoulder and hip vertical displacement and trunk inclination were calculated for a complete stroke. Paired t-test revealed that while the trunk inclination displayed no significant difference to freestyle when performing the *Long Dog* drill ($p < 0.05$), the upper-limb kinematics varied for different swimmers. Similarly, the *Polo* drill results displayed both similar and different stroke signatures between freestyle and *Polo* drill swimming illustrating that drills can influence the stroke kinematics differently depending on the swimmer and distance specialisation. Overall, the findings suggest that individual-based analysis should form part of the biomechanical assessment of swimming performance, especially at the elite level, because certain drills may not be as beneficial for particular swimmers.

6.2 Introduction

In elite swimming, training programs are typically individualised in order to support the individual differences that exist between athletes (Brackley, Barris, et al., 2020; Junggren et al., 2018; Nicol, Ball, & Tor, 2019). However, the specific practice tasks prescribed to improve or condition swimming skills have not been empirically investigated. Group-based analyses have provided useful information related to the effect drill swimming has on freestyle performance (see Chapter 5) (Arellano et al., 2010; Brackley, Tor, et al., 2020; López et al., 2002). However, individual-based analysis is required in order to provide insights as to how drills can affect freestyle stroke kinematics differently per individual athlete base on their skill level and physical characteristics.

Individual analysis is a single-subject analysis which is important in the biomechanical assessment of skill movement (Ball & Best, 2012; Ball et al., 2003a; Bates et al., 2004; Dufek et al., 1995). Analysis results by individual can provide important information that might be masked in a group-based analysis (Ball & Best, 2012; Ball et al., 2003a; Bates et al., 2004; Dufek et al., 1995). Ball and Best (2012) reported individual-specific relationships in centre of pressure parameters and golf club head velocity. When looking at weight transfer in the golf swing, golfers returned different combinations of significant factors that were not evident in the group-based analysis (Ball & Best, 2007). As these factors would not have been identified using only group-based analysis, the possibility to offer technique recommendations specific to the individual would have been hindered (Ball & Best, 2012).

Researchers have highlighted the need to include individual-based analysis when biomechanically examining swimming parameters, especially at the high-performance level (Button et al., 2006; Nicol et al., 2019; Tor et al., 2018). Tor et al. (2018) investigated the underwater trajectory of the swimming start using an individual-based analysis approach to illustrate the non-linear and individualised learning responses of three elite swimmers. This study supports the suggestion that individual-based analysis provides a clearer picture of how performers exploit variability and is considered most appropriate for the individual in terms of skill development (Ball et al., 2003a; Button et al., 2006).

There is further evidence for the importance of individual-specific analysis in rifle shooting (Ball et al., 2003a) and air pistol shooting (Ball et al., 2003b). Ball et al. (2003a) identified individual-specific body sway and performance relationships whereas the group-based analysis returned no significant correlations. Additionally, in elite diving, Barris, Farrow, et al. (2013) examined differences of completed dives and those of baulked take-offs on an individual basis ($n = 6$). While there were no observable differences between performance conditions for all participants, individual differences were observed in the hurdle and approach phases (Barris, Farrow, et al., 2013). Consequently, individualised analysis can provide unique insights into how elite individuals perform and adjust movement responses. From a dynamical systems theory perspective, individual-based analysis of kinematics is also preferred in order to unravel the complex processes governing motor control (Button et al., 2006). Further, practice tasks should be designed based on the specific needs of the athlete, allowing key interactions with the environment to be maintained (Pinder & Renshaw, 2019).

Elite swimming coaches have acknowledged that practice design should be individualised (Brackley, Barris, et al., 2020). However, the commonly prescribed practice drills tend to promote a standard biomechanical model of ‘good’ technique. This mechanist view of human behaviour can fail to consider the wide array of constraints which impinge on an individual’s learning and performance (Brackley, Barris, et al., 2020; Davids et al., 2017; Seifert et al., 2013).

Understanding the underlying skill acquisition approaches adopted by elite swimming coaches can provide context to explain which freestyle drills are typically being prescribed, and the rationale for why (see Chapter 3) (Brackley, Barris, et al., 2020). The purpose of this study was to extend the findings in Study Two (Chapter 5) and use an individual-based approach to measure the key movement and stroke phases when drill swimming. The specific aims were to (i) compare the kinematics of full freestyle and the *Long Dog* drill in the pull and push phases of the stroke on an individual basis and (ii) compare the kinematics of full freestyle and the *Polo* drill freestyle in the entry and catch, pull and push phases of the stroke on an individual basis. Individual differences were expected given the swimmers' freestyle distance specialisation in addition to their own anthropometric, mechanical and physiological characteristics (Seifert, Button, et al., 2010; Seifert et al., 2013).

6.3 Methods

The methodological procedures undertaken have been detailed in Chapter 4 (see section 4.2 – 4.7, p. 88 - 113) and are repeated here for clarity and to allow the chapter to read as a standalone article. However, the identification of the stroke cycle phases was altered for the *Long Dog* drill trials, as detailed in section 6.3.3, p. 175. Further, while the statistical methods undertaken remained unaltered, the procedures comprised of six separate analyses for each individual participant.

6.3.1 Participants

Six elite freestyle swimmers (4 male, 2 female, age 19.67 ± 2.75 years, Fédération Internationale de Natation (FINA) points 844 ± 59), who competed at a national and international standard, volunteered to participate in this study. The criteria for participation were as follows: (i) attended national and international level competitions on a regular basis, (ii) have a minimum of two years specialised in their chosen distance as a freestyle swimmer and (iii) have no injuries nor be in the process of recovery at the time of testing. The specified selection criteria were based on an increased likelihood that such participants had well established freestyle stroke characteristics (McCabe & Sanders, 2012; Nikodelis et al., 2005; Pyne et al., 2004). The characteristics of the freestyle specialists are presented in Table 6.1. The study and test procedures were approved by the Victoria University Human Research Ethics Committee (see Appendix B - Participants information and consent). All participants received a full explanation of the nature of the study and (or a parent/guardian when a participant was under 18 years old) provided signed written informed consent prior to the testing procedures.

Table 6.1 Participant information and general physical characteristics.

Participant	Gender	Age (yrs.)	Height (cm)	Mass (kg)	Distance specialisation
SW1	Male	17	185.80	73.00	Sprint
SW2	Female	16	166.50	70.38	Middle
SW3	Male	19	190.90	84.00	Long*
SW4	Male	24	196.10	88.00	Sprint
SW5	Female	20	178.00	77.30	Middle
SW6	Male	22	190.00	90.10	Long

Sprint = 50 - 100m, Middle = 200 - 400m and Long ≥ 400 m
*Open water and long-distance specialist.

Black markers (36 mm in diameter) were affixed on the right and left side of each participant to enable the identification and tracking of anatomical landmarks. Through pilot testing, black markers were found to offer the best contrast and could most easily be seen in the underwater environment. Marker sites included the tip of the third distal phalanx, styloid process of the lunar and radius, olecranon process of the ulna, greater tubercle of the humerus, greater trochanter, lateral epicondyle of the femur, lateral malleolus, fifth metatarsophalangeal joint and first interphalangeal joint.

6.3.2 Testing procedure and setup

The testing procedures took place in a four-lane 25 m level deck, indoor pool with an average pool temperature of 26°C. After a personalised warm-up, each participant was required to perform the two commonly prescribed upper-limb freestyle drills, *Long Dog* and *Polo*, in randomised order. The testing protocol for each drill required participants to swim a total of 300 m broken into 2 x 25 m drill then 2 x 25 m laps of freestyle swimming, repeated three times. The participants were instructed to perform the drill and swim trials at a similar pace they would in training, beginning with a push start and taking rests as required (McCabe et al., 2011). Given previous studies have indicated that the dive and tumble turn action influences stoke kinematics, participants were further instructed to avoid performing the traditional tumble turn at the end of each 25 m lap (Takeda et al., 2009; Veiga & Roig, 2017). No additional feedback or instructions were given on their performance.

The swimmer's movements were captured in the middle of the pool within an 8.91 m^3 pre-calibrated volume. The volume was calibrated using a rectangular prism frame of the following dimensions: 6.0 m length (*x*-axis), 1.0 m width (*y*-axis) and 1.5 m height (*z*-axis). The calibration frame contained seventy black circular calibration markers (36 mm in diameter) and was positioned to allow 0.5 m (*z*-axis) above-water and 1.0 m (*z*-axis) underwater with the *x*-axis aligned with the swimming direction (Figure 6.1) (for more detail see Chapter 4, Figure 4.5 and 4.6, p. 95). The accuracy of the marker positions was validated using a seven–camera motion analysis system (T40 series, Vicon Nexus, Oxford, UK) in an indoor controlled area. The cameras were mounted at a height of 1.5 ± 0.9 m and placed in an arc around the frame. Reflective markers where attached to the centre of each of the marker locations on the frame. The accuracy of the marker locations was 0.03 mm for *x*-, *y*- and *z*-axes, respectively.

The calibration frame and swimming movement was captured using eight stationary cameras (SwimPro®, NSW, Australia), four above- and four below-water, operating at a sample frequency of 30 Hz. The cameras were mounted onto four separate camera mounts which enabled one camera to record above-water and one camera to record underwater. The images were synchronised using a pair of lights visible in the field of each camera. Each camera was positioned and adjusted to ensure that the field of view of each camera was approximately 8.0 m long, extending at least 1.0 m beyond each side of the 6.0 m long calibration frame on the *x*-axis (Figure 6.1). The rationale behind recording a space of at least 8.0 m long was to ensure that no calibration points within the calibration frame were lost during the correction of the cameras' lens distortions (Beardsley et al., 1992; Remondino & Fraser, 2006; Silvatti et al., 2013; Zhang, 1998). The bespoke Matlab (MathWorks, Natick, MA, USA) program, Cinalysis (Elipot et al., 2010a), was used to manually digitise the recorded calibration frame to yield separate calibration files for the above- and underwater views. The Cinalysis program was designed specifically for 3D analysis in swimming and has been used in previous research (Elipot et al., 2010a; Papic et al., 2020). The root mean square (RMS) reconstruction error of the validation points on the calibration frame were as follows for the *x*, *y*, *z* axis, respectively: 4.7 mm, 3.6 mm and 4.9 mm for the above-water calibration space and 4.5 mm, 3.8 mm and 6.2 mm for the below water calibration space. For full explanation of the camera setup and calibration process, refer to Chapter 4, section 4.3.2, p. 91 and section 4.3.3, p. 97 respectively.

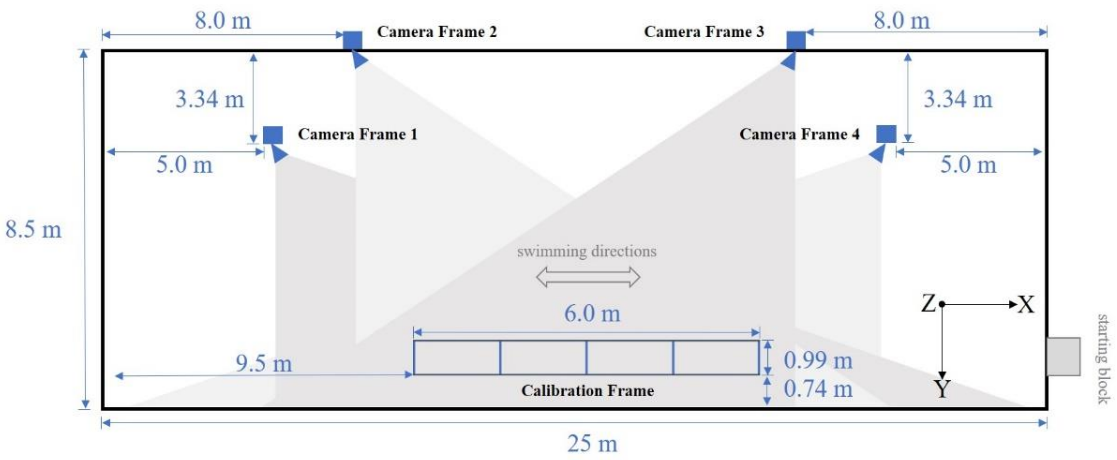


Figure 6.1 Representation of experimental setup with one camera above-water and one underwater per camera mount.

6.3.3 Data processing

To kinematically analyse the freestyle and drill swimming technique, one complete stroke cycle was selected for each of the twelve 25 m swim laps per drill protocol and swimmer. This included six drill and six freestyle stroke cycles per drill and participant. One complete stroke cycle is commonly defined as the period between the entry and re-entry of the same hand. However, as the hand did not exit the water in *Long Dog* drill swimming, one stroke cycle was defined as the period between the beginning of the pull and the consecutive pull start of the same hand. Depending on the swimming direction, either the right or left side of the swimmer was digitised. The trials analysed consisted of a combination of right- and left-handed stroke cycles both between and within participants. Selected body landmarks on each swimmer were manually digitised using the Cinalysis program (Elipot et al., 2010a). These specific landmarks were limited to the tip of the third distal phalanx, styloid process of the lunar and radius, olecranon process of the ulna, greater tubercle of the humerus and the greater trochanter. The direct linear transformation (DLT) method was used to reconstruct the digitised files into a single file containing the continuous 3D coordinates for each body landmark (Abdel-Aziz & Karara, 1971). The raw displacement, velocity and acceleration data were displayed in separate tabs within the file.

A second-order Butterworth filter, with cut-off frequencies ranging between 3 and 8 Hz, was used to filter the raw data (Winter, 1990). Cut-off frequencies were chosen based on residual analysis where the 3D coordinate data of each digitised landmark were filtered separately (Bartlett, 2014; Schreven et al., 2015; Winter, 2009). The selection of each cut-off frequency comprised of finding the breakpoints in the residual curve. A conservative approach was taken meaning that a higher cut-off frequency was selected to allow an amount of noise through the filter in order to avoid losing valuable data (Winter, 2009). Visual inspection of the data also confirmed that the smoothed data did not remove valuable maxima and minima data points. A more detailed description of the data processing techniques and methods can be found in Chapter 4, section 4.5 p. 103.

6.3.4 Data analysis

In line with previous freestyle swimming research, four separate phases within the stroke cycle were identified: (i) entry and catch, (ii) pull, (iii) push and (iv) recovery (Chollet et al., 2000; de Jesus et al., 2012). The description of how the phases within the stroke cycle were defined are detailed in Chapter 4, Table 4.8, p. 110. The entry and catch phase was identified from the first frame the finger broke the water surface, on initial hand entry, to the first frame the finger began to move horizontally backwards The sum of the pull and push phases was considered as the main propulsive phase of the stroke cycle (Chollet et al., 2000; Gourgoulis et al., 2014). Further, the sum of the entry and catch, pull and push phases were defined as the underwater phase of the stroke cycle. While Koga et al. (2020) recently demonstrated that the entry and catch phase contributes to forward propulsion, this study followed the methods outlined by Chollet et al. (2000) in identifying the stroke phases.

The temporal and upper-limb parameters measured are detailed in Table 6.2. The average horizontal velocity of the hip was used to estimate the average horizontal swimming velocity (SV) during one stroke cycle (Gourgoulis, Aggeloussis, Vezos, et al., 2008; Gourgoulis et al., 2014). Evidence within the literature has confirmed that the use of the hip instead of the centre of mass to estimate SV has a tendency to either under- or overestimate velocity values (Fernandes et al., 2012; Figueiredo et al., 2009; Psycharakis & Sanders, 2009). However, the specific anatomical landmarks digitised for this study limited the centre of mass to be estimated. Consequently, when using the hip as a measure of SV and/or displacements, Fernandes et al. (2012) recommended that the hip point error magnitude needs to be taken into consideration in the interpretation of the results.

Table 6.2 Measured temporal and upper-limb displacement parameters, along with parameter definitions.

Parameter	**Definition**
Swimming velocity (SV) (m/s)	The average horizontal velocity of the hip during one stroke cycle.
Stroke length (SL) (m)	The horizontal displacement of the hip during a complete stroke cycle.
Stroke rate (SR) (cycles/min)	The inverse of time (minutes) to complete one stroke cycle.
Stroke index (SI) (m^2/s)	Stroke length multiplied by swimming velocity.
Upper-limb lateral motion (m)	The *y*-displacement of the finger, wrist and elbow.
Upper-limb vertical motion (m)	The *z*-displacement of the finger, wrist and elbow.

The elbow flexion/extension angle was quantified as the arc-cosine of the dot product of the upper arm (*a*) and lower arm (*b*) unit vectors (Equation 6.1) (McCabe et al., 2011;

McCabe & Sanders, 2012). The elbow angle was quantified at four instances within the stroke cycle: (i) hand entry, (ii) beginning of finger moving horizontally backwards, (iii) finger vertically aligned with shoulder and (iv) end of backwards movement (McCabe et al., 2011).

$$elbow\ angle = \text{acos}\left(\frac{a \cdot b}{|a||b|}\right) \qquad \textbf{[6.1]}$$

The trunk was defined as the segment formed between the shoulder ($S_{houlder}$) and hip (H_{ip}). Therefore, to assess body alignment, the trunk inclination was calculated as the angle between the trunk and the horizontal plane and was estimated according to Equation 6.2 (Zamparo et al., 2009).

$$trunk\ inclination = arctan\frac{(s_{houlder} - H_{ip})_z}{(s_{houlder} - H_{ip})_x} \qquad \textbf{[6.2]}$$

6.3.5 Digitising reliability

Two operators digitised the swim trials of the six participants. The operators received demonstrations and underwent training to gain familiarity and accuracy with the Cinalysis program. To assess the intra- and inter-reliability (i.e., within and between operator reliability) of the two operators' digitising technique, a single stroke cycle (randomly selected) was digitised five times for all eight camera views (Osborough et al., 2015). Digitising was conducted on separate days with no repeats of the same camera view on the same day. This ensured that reliability was not artificially improved by familiarity due to the practice effect of identifying the anatomical landmarks (Sanders, Gonjo, et al., 2015).

6.3.6 Statistical analysis

To compare differences between freestyle and drill swimming for each variable, a paired t-test was used. As there were a large number of tests, the *p*-value was initially set at a confidence level of $p < 0.05$ and then adjusted using the Bonferroni–Holm correction (Harrison et al., 2020; Holm, 1979). Previous swimming studies have also used the Bonferroni-Holm correction to control for multiple comparison tests (Issurin et al., 2014; Martens et al., 2015). The Bonferroni–Holm procedure reduces the apparent significant of effects by adjusting the rejection criteria for each test. Specifically, the *p*-values are sorted from smallest to largest. Using Equation 6.3, the *p*-value was adjusted for each test. If the *p*-value was greater or equal to adjusted *p*-value, then the *p*-value was not significant. However, if the first *p*-value was smaller than the adjusted *p*-value, than the *p*-value was declared significant.

$$P^{B\text{-}H} = \frac{\alpha}{n} \qquad \textbf{[6.3]}$$

Where $P^{B\text{-}H}$ is the adjusted *p*-value using Bonferroni-Holm correction, α is the initial *p*-value and n is the number of tests remaining.

Prior to comparative analysis, the normality of each calculated variable was checked using the Shapiro-Wilk test. As some variables were not normally distributed, the paired samples Wilcoxon test was used as a non-parametric alternative of the paired t-test for the statistical treatment of those variables (Harrison et al., 2020). All processed data were analysed using R studio (R Core Team, 2016) and kinematic data reported as mean values and standard deviations.

The effect size was calculated using Cohen's *d* to describe the magnitude of difference. The interpretation of the effect size for each variable was calculated in accordance to Cohen (1988) which evaluates the magnitude of differences between two means. Specifically, Cohen's *d* expressed mean differences between two groups in standard deviation units whereby if the calculated *d* equals zero, then the mean of the difference scores is equal to zero. As *d* deviates from zero, the effect size becomes larger. Accordingly, if the absolute value of Cohen's *d* was between less than 0.2 it was considered a very small effect, 0.2 to 0.3 was considered as a small effect size, 0.3 to 0.5 was moderate and greater than 0.5 was considered a large effect.

6.4 Results

6.4.1 Long Dog drill

All participants showed significantly lower average SV and stroke rate (SR) values when performing the *Long Dog* drill whereas the total stroke duration displayed significantly higher average values (Table 6.3). Only one participant displayed a significantly lower average pull duration, returning a large effect size, when performing the *Long Dog* drill. The push phase duration presented significant differences between freestyle and *Long Dog* drill swimming for four participants with three producing a shorter duration and one displaying a longer duration, all returning large effect sizes. Four participants showed significantly shorter average relative propulsive duration values when *Long Dog* drill swimming and returned large effect sizes. At the catch instant, *Long Dog* drill swimming showed significantly less elbow flexion for two participants and returned large effect sizes. Further, one participant displayed less elbow flexion at the shoulder instant, returning a large effect size. Conversely, at the release instant, one participant demonstrated greater elbow flexion and the effect size was large.

Table 6.3 Individual-based mean temporal race performance variables, relative duration of stroke phases and elbow angle parameters between freestyle and the *Long Dog* drill.

Participant	Variable	Freestyle	*Long Dog*	P	P^{B-H}	*d*
SW1 (Male)	**Swimming velocity** (m/s)	0.99 ± 0.03	0.80 ± 0.04	< 0.001*	0.001	5.02
	Stroke length (m)	2.10 ± 0.08	2.05 ± 0.15	0.35	0.010	0.40
	Stroke rate (cycles/min)	28.20 ± 0.03	23.40 ± 0.02	< 0.001*	0.001	2.95
	Total duration of SC (s)	2.14 ± 0.013	2.54 ± 0.13	< 0.001*	0.001	3.06
	Pull (% of SC)	12.94 ± 1.01	12.21 ± 0.70	0.02	0.004	0.84
	Push (% of SC)	14.16 ± 2.17	12.78 ± 1.46	0.03	0.005	0.75
	Propulsive phase (%)	27.10 ± 2.37	24.99 ± 2.05	< 0.001*	0.001	0.95
	Elbow angle at catch (°)	152.2 ± 8.5	157.1 ± 7.7	0.14	0.006	0.61
	Elbow angle at shoulder (°)	107.7 ± 1.9	110.0 ± 4.0	0.09	0.005	0.75
	Elbow angle at release (°)	142.8 ± 7.5	147.6 ± 10.3	0.21	0.007	0.54
SW2 (Female)	**Swimming velocity** (m/s)	0.88 ± 0.03	0.79 ± 0.04	< 0.001*	0.001	2.79
	Stroke length (m)	1.94 ± 0.08	1.96 ± 0.11	0.46	0.017	0.27
	Stroke rate (cycles/min)	27.00 ± 0.01	24.00 ± 0.03	< 0.001*	0.001	2.24
	Total duration of SC (s)	2.20 ± 0.05	2.52 ± 0.20	< 0.001*	0.001	2.17
	Pull (% of SC)	11.88 ± 1.76	10.31 ± 1.20	0.01	0.003	1.04
	Push (% of SC)	13.90 ± 0.83	13.38 ± 2.16	0.41	0.010	0.32
	Propulsive phase (%)	25.79 ± 2.12	23.68 ± 2.32	0.06	0.006	0.95
	Elbow angle at catch (°)	149.1 ± 7.1	152.3 ± 5.5	0.25	0.010	0.50
	Elbow angle at shoulder (°)	102.2 ± 8.7	107.8 ± 15.4	0.07	0.004	0.45
	Elbow angle at release (°)	143.6 ± 3.7	144.4 ± 13.1	0.83	0.050	0.08
SW3 (Male)	**Swimming velocity** (m/s)	0.98 ± 0.05	0.87 ± 0.03	< 0.001*	0.001	2.91
	Stroke length (m)	2.27 ± 0.09	2.27 ± 0.10	0.29	0.010	0.01
	Stroke rate (cycles/min)	25.80 ± 0.01	22.80 ± 0.03	< 0.001*	0.003	2.96
	Total duration of SC (s)	2.31 ± 0.06	2.62 ± 0.14	< 0.001*	0.003	2.87
	Pull (% of SC)	9.34 ± 0.73	9.96 ± 0.67	0.01	0.004	0.89
	Push (% of SC)	13.80 ± 1.12	10.58 ± 1.29	< 0.001*	0.001	2.67
	Propulsive phase (%)	23.15 ± 1.59	20.54 ± 1.15	< 0.001*	0.002	1.88
	Elbow angle at catch (°)	138.7 ± 10.9	149.5 ± 9.7	< 0.001*	0.003	1.05
	Elbow angle at shoulder (°)	123.0 ± 10.1	123.7 ± 9.0	0.47	0.017	0.08
	Elbow angle at release (°)	142.2 ± 5.5	127.6 ± 7.1	< 0.001*	0.003	2.30
SW4 (Male)	**Swimming velocity** (m/s)	0.97 ± 0.03	0.73 ± 0.05	< 0.001*	0.002	6.35
	Stroke length (m)	2.25 ± 0.05	2.13 ± 0.13	0.04	0.005	1.29
	Stroke rate (cycles/min)	26.40 ± 0.01	20.40 ± 0.01	< 0.001*	0.002	6.74
	Total duration of SC (s)	2.29 ± 0.07	2.94 ± 0.13	< 0.001*	0.002	6.22
	Pull (% of SC)	11.67 ± 0.95	10.59 ± 0.90	< 0.001*	0.002	1.18
	Push (% of SC)	0.29 ± 0.04	0.36 ± 0.03	< 0.001*	0.002	1.82
	Propulsive phase (%)	24.53 ± 1.20	22.67 ± 0.42	< 0.001*	0.002	2.07
	Elbow angle at catch (°)	150.2 ±5.2	152.8 ± 8.8	0.30	0.013	0.36
	Elbow angle at shoulder (°)	111.3 ± 4.3	115.6 ± 6.4	0.03	0.004	0.80
	Elbow angle at release (°)	140.1 ± 9.9	152.2 ± 10.3	0.01	0.004	1.19
SW5 (Female)	**Swimming velocity** (m/s)	0.89 ± 0.04	0.72 ± 0.02	< 0.001*	0.002	5.25
	Stroke length (m)	1.84 ± 0.10	1.78 ± 0.07	0.45	0.017	0.63
	Stroke rate (cycles/min)	29.40 ± 0.01	24.00 ± 0.01	< 0.001*	0.002	12.08
	Total duration of SC (s)	2.06 ± 0.03	2.48 ± 0.04	< 0.001*	0.002	12.41
	Pull (% of SC)	10.38 ± 2.36	11.29 ± 1.37	0.24	0.007	0.47
	Push (% of SC)	14.94 ± 2.63	12.63 ± 0.72	< 0.001*	0.002	1.20
	Propulsive phase (%)	25.31 ± 2.06	23.91 ± 1.89	0.05	0.006	0.71
	Elbow angle at catch (°)	146.4 ± 9.1	127.8 ± 45.6	0.77	0.025	0.57
	Elbow angle at shoulder (°)	111.3 ± 5.7	77.8 ± 43.8	0.08	0.005	1.07
	Elbow angle at release (°)	141.7 ± 11.9	122.1 ± 35.5	0.10	0.006	0.74
SW6 (Male)	**Swimming velocity** (m/s)	1.05 ± 0.07	0.93 ± 0.06	< 0.001*	0.002	1.86
	Stroke length (m)	2.47 ± 0.19	2.57 ± 0.16	0.01	0.004	0.55
	Stroke rate (cycles/min)	25.80 ± 0.01	21.60 ± 0.01	< 0.001*	0.002	8.29
	Total duration of SC (s)	2.34 ± 0.04	2.77 ± 0.07	< 0.001*	0.003	7.66
	Pull (% of SC)	11.06 ± 0.59	11.11 ± 0.44	0.75	0.050	0.10
	Push (% of SC)	13.04 ± 0.62	10.92 ± 1.37	< 0.001*	0.003	1.99
	Propulsive phase (%)	24.10 ± 0.97	22.03 ± 1.71	< 0.001*	0.003	1.48
	Elbow angle at catch (°)	138.7 ± 31.6	162.2 ± 2.8	< 0.001*	0.003	1.04
	Elbow angle at shoulder (°)	87.3 ± 34.3	106.3 ± 3.4	< 0.001*	0.003	0.78
	Elbow angle at release (°)	123.4 ± 44.0	141.1 ± 6.1	0.22	0.008	0.56

Data expressed as mean ± standard deviation, % difference (freestyle vs. *Long Dog* drill swimming), *p*-value, Bonferroni-Holm correction *p*-value and effect size.
*indicates a significant difference between freestyle and *Long Dog* drill swimming, using Bonferroni-Holm correction.
SC denotes stroke cycle.
P^{B-H} denotes Bonferroni-Holm correction *p*-value.

Figure 6.2 and 6.3 illustrates the frontal view of the lateral and vertical finger displacement between freestyle and *Long Dog* drill swimming for each individual swimmer on the right- and left-handed stroke cycles, respectively. Qualitatively, the figures demonstrate the presence of inter-trial variability of the finger's trajectory. However, the individual stroke signatures display intra-individual similarities in the finger trajectory between freestyle and *Long Dog* drill swimming for all participants.

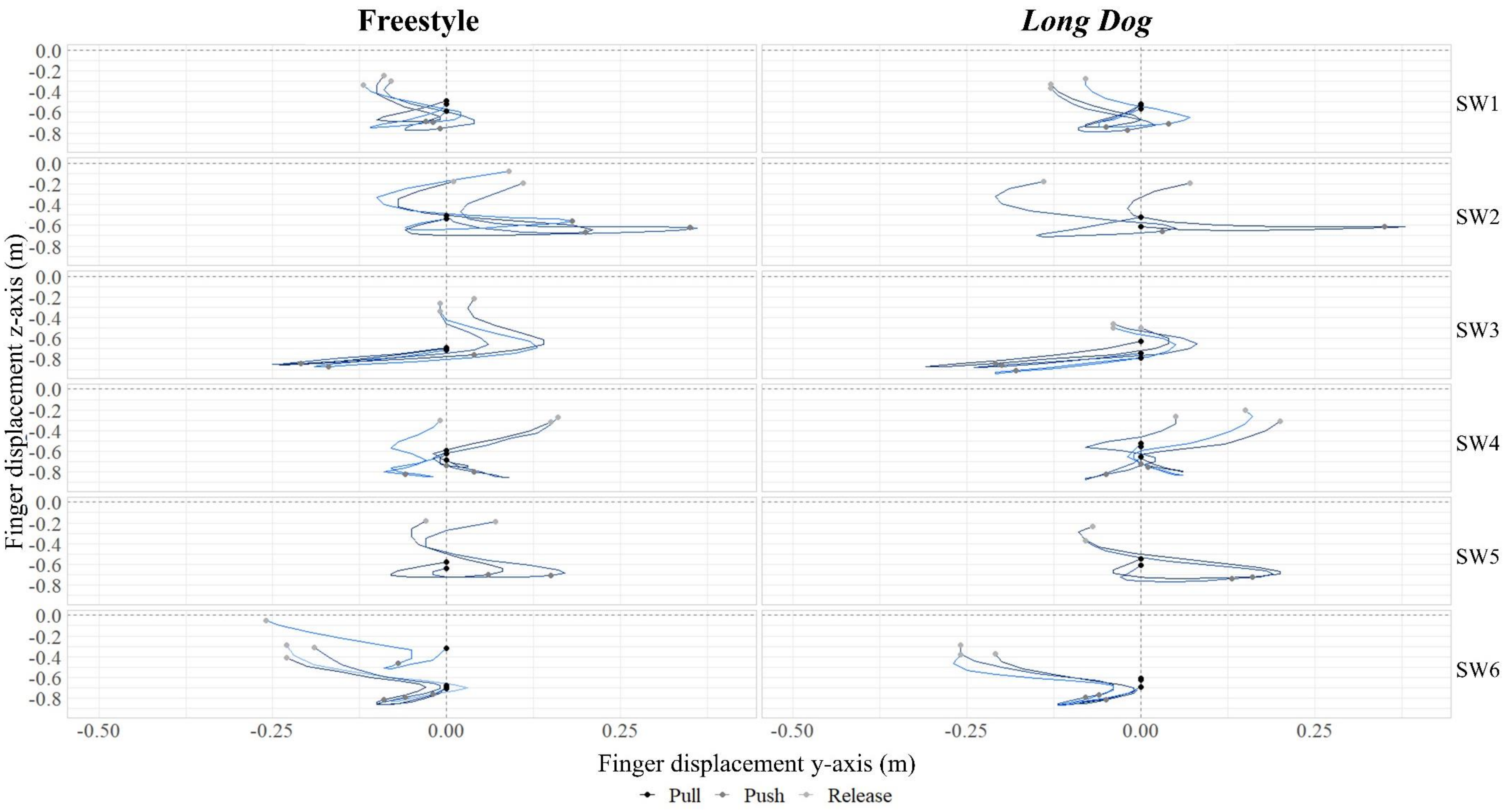


Figure 6.2 Frontal view of the right finger's underwater trajectory for each individual participant during freestyle and *Long Dog* drill swimming.

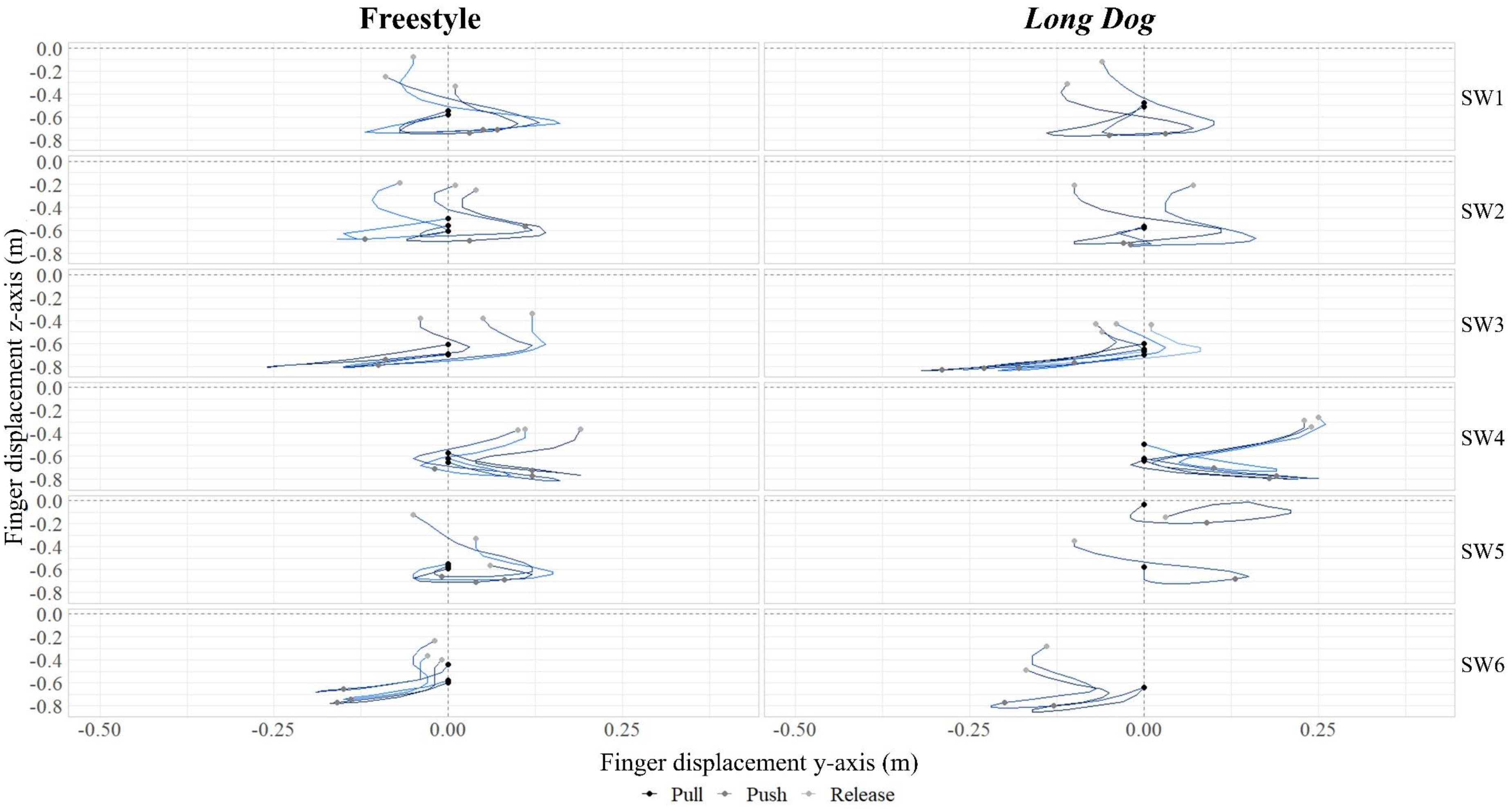


Figure 6.3 Frontal view of the left finger's underwater trajectory for each individual participant during freestyle and *Long Dog* drill swimming.

6.4.1.1 Pull phase

The *Long Dog* drill produced a significantly slower hip velocity in the pull phase of the stroke cycle for all participants, returning large effect sizes (Table 6.4). Three participants displayed significant differences in finger velocity with two participants showing lower average values and one displaying a higher average value when performing the *Long Dog* drill. Two participants displayed significantly deeper maximal finger displacement values when performing the *Long Dog* drill. One participant showed a significantly larger finger lateral range, returning a moderate effect size. Further, when *Long Dog* drill swimming, one participant produced a significantly smaller lateral range of the wrist and returned a large effect size. Two participants displayed significant differences in the elbow lateral range with one participant producing a smaller range and the other producing a larger range. *Long Dog* drill swimming also produced greater hip vertical range values within the pull phase of the stroke for two participants and returned large effect sizes. Only one participant displayed a significantly greater trunk inclination when *Long Dog* drill swimming and the effect size was large.

Table 6.4 Kinematic parameters within the pull phase of the stroke between freestyle and the *Long Dog* drill.

Participant		Variable	Freestyle	*Long Dog*	P	$P^{B\text{-}H}$	*d*
SW1 (Male)	*Pull*	**Finger velocity** (m/s)	1.21 ± 0.09	1.24 ± 0.14	0.56	0.025	0.24
		Hip velocity (m/s)	1.20 ± 0.03	0.99 ± 0.06	< 0.001*	0.002	4.81
		Max finger vertical displacement (m)	0.74 ± 0.03	0.76 ± 0.02	0.02	0.002	1.03
		Finger lateral range (m)	0.12 ± 0.03	0.11 ± 0.03	0.36	0.003	0.30
		Wrist lateral range (m)	0.10 ± 0.01	0.07 ± 0.03	< 0.001*	0.001	1.63
		Elbow lateral range (m)	0.14 ± 0.03	0.12 ± 0.02	< 0.001*	0.001	1.05
		Shoulder vertical range (m)	0.07 ± 0.01	0.07 ± 0.02	0.79	0.010	0.10
		Hip vertical range (m)	0.15 ± 0.02	0.16 ± 0.02	0.01	0.003	0.74
		Trunk inclination (°)	10.50 ± 2.22	10.54 ± 2.28	0.96	0.050	0.02
SW2 (Female)	*Pull*	**Finger velocity** (m/s)	0.95 ± 0.21	1.13 ± 0.17	< 0.001*	0.002	0.94
		Hip velocity (m/s)	1.15 ± 0.03	0.92 ± 0.04	< 0.01*	0.006	6.04
		Max finger vertical displacement (m)	0.68 ± 0.02	0.71 ± 0.04	0.03	0.002	0.96
		Finger lateral range (m)	0.20 ± 0.10	0.19 ± 0.14	0.55	0.004	0.15
		Wrist lateral range (m)	0.10 ±0.04	0.12 ± 0.03	0.22	0.003	0.46
		Elbow lateral range (m)	0.10 ± 0.05	0.10 ± 0.02	0.82	0.006	0.09
		Shoulder vertical range (m)	0.04 ± 0.02	0.03 ± 0.02	1.89	0.050	0.48
		Hip vertical range (m)	0.12 ± 0.02	0.12 ± 0.02	0.75	0.007	0.08
		Trunk inclination (°)	12.47 ± 2.15	12.10 ± 2.44	0.60	0.013	0.16
SW3 (Male)	*Pull*	**Finger velocity** (m/s)	1.54 ± 0.05	1.30 ± 0.21	< 0.001*	0.003	1.60
		Hip velocity (m/s)	1.22 ± 0.06	1.08 ± 0.14	0.01*	0.006	1.23
		Max finger vertical displacement (m)	0.83 ± 0.03	0.86 ± 0.04	< 0.001*	0.001	0.83
		Finger lateral range (m)	0.26 ± 0.04	0.29 ± 0.05	0.05	0.002	0.60
		Wrist lateral range (m)	0.20 ± 0.03	0.22 ± 0.03	0.03	0.002	0.71
		Elbow lateral range (m)	0.16 ± 0.02	0.17 ± 0.03	0.10*	0.002	0.53
		Shoulder vertical range (m)	0.05 ± 0.02	0.05 ± 0.02	0.47	0.006	0.21
		Hip vertical range (m)	0.10 ± 0.01	0.12 ± 0.02	< 0.001*	0.002	1.69
		Trunk inclination (°)	1.78 ± 0.48	2.76 ± 0.81	< 0.001*	0.004	1.48
SW4 (Male)	*Pull*	**Finger velocity** (m/s)	1.26 ± 0.11	1.18 ± 0.07	0.02	0.008	0.88
		Hip velocity (m/s)	1.27 ± 0.06	0.95 ± 0.05	< 0.001*	0.003	5.91
		Max finger vertical displacement (m)	0.80 ± 0.04	0.80 ± 0.04	0.58	0.004	0.16
		Finger lateral range (m)	0.11 ± 0.07	0.15 ± 0.09	< 0.001*	0.001	0.53
		Wrist lateral range (m)	0.11 ± 0.03	0.12 ± 0.05	0.93	0.003	0.12
		Elbow lateral range (m)	0.16 ± 0.03	0.16 ± 0.01	0.83	0.007	0.07
		Shoulder vertical range (m)	0.06 ± 0.02	0.06 ± 0.02	0.80	0.017	0.09
		Hip vertical range (m)	0.13 ± 0.02	0.13 ± 0.02	0.64	0.006	0.17
		Trunk inclination (°)	12.16 ± 2.53	12.10 ± 2.40	0.94	0.025	0.02
SW5 (Female)	*Pull*	**Finger velocity** (m/s)	1.00 ± 0.11	0.95 ± 0.12	0.32	0.013	0.44
		Hip velocity (m/s)	1.20 ± 0.03	0.98 ± 0.06	< 0.001*	0.004	5.06
		Max finger vertical displacement (m)	0.70 ± 0.02	0.58 ± 0.26	1.00	0.025	0.66
		Finger lateral range (m)	0.12 ± 0.04	0.14 ± 0.03	0.02	0.002	0.72
		Wrist lateral range (m)	0.07 ± 0.02	0.06 ± 0.03	0.20	0.002	0.53
		Elbow lateral range (m)	0.09 ± 0.01	0.09 ± 0.03	1.00	0.050	0.00
		Shoulder vertical range (m)	0.03 ± 0.01	0.04 ± 0.01	0.01	0.004	1.36
		Hip vertical range (m)	0.06 ± 0.02	0.05 ± 0.03	0.80	0.025	0.13
		Trunk inclination (°)	16.67 ± 2.14	14.92 ± 1.00	0.07	0.006	1.05
SW6 (Male)	*Pull*	**Finger velocity** (m/s)	1.33 ± 0.10	1.25 ± 0.04	< 0.001*	0.004	1.11
		Hip velocity (m/s)	1.30 ± 0.03	1.06 ± 0.03	< 0.001*	0.005	7.36
		Max finger vertical displacement (m)	0.76 ± 0.12	0.85 ± 0.02	< 0.001*	0.001	1.08
		Finger lateral range (m)	0.13 ± 0.04	0.14 ± 0.05	0.01	0.001	0.31
		Wrist lateral range (m)	0.12 ± 0.05	0.13 ± 0.04	0.34	0.003	0.20
		Elbow lateral range (m)	0.20 ± 0.02	0.22 ± 0.02	< 0.001*	0.001	1.21
		Shoulder vertical range (m)	0.05 ± 0.02	0.06 ± 0.02	0.18	0.005	0.59
		Hip vertical range (m)	0.14 ± 0.01	0.16 ± 0.01	< 0.001*	0.003	1.27
		Trunk inclination (°)	10.81 ± 1.98	10.08 ± 1.41	0.21	0.008	0.43

Data expressed as mean ± standard deviation, % difference (freestyle vs. *Long Dog* drill swimming), *p* value, Bonferroni-Holm correction *p*-value and effect size.
*indicates a significant difference between freestyle and *Long Dog* drill swimming, using Bonferroni-Holm correction.
$P^{B\text{-}H}$ denotes Bonferroni-Holm correction *p*-value.

6.4.1.2 Push phase

In the push phase, performing the *Long Dog* drill produced significantly slower average finger velocity values for two participants and higher average finger velocity values for one participant (Table 6.5). Further, the average hip velocity was significantly slower for all participants, returning large effect sizes. The *Long Dog* drill only showed a significantly deeper maximum finger displacement for one participant, returning a moderate effect size. Two participants displayed significant differences in the finger lateral range with one participant producing a smaller range and the other a larger range when performing the *Long Dog* drill, all returning large effect sizes. When performing the *Long Dog* drill, the lateral range of the wrist and elbow presented significantly smaller average values for two participants and returned large effect sizes. Four participants displayed a significantly greater vertical range in the shoulder when performing the *Long Dog* drill. Two participants also displayed significant differences in hip vertical range values with one participant displaying a large range and the other a smaller range. Two participants displayed significantly less trunk inclination when performing the *Long Dog* drill compared to freestyle, returning large effect sizes.

Table 6.5 Kinematic parameters within the push phase of the stroke between freestyle and the *Long Dog* drill.

Participant		Variable (°)	Freestyle	*Long Dog*	P	$P^{B\text{-}H}$	*d*
SW1 (Male)	***Push***	**Finger velocity** (m/s)	1.28 ± 0.31	1.33 ± 0.11	0.55	0.017	0.20
		Hip velocity (m/s)	1.37 ± 0.02	1.27 ± 0.06	< 0.001*	0.002	2.12
		Max finger vertical displacement (m)	0.72 ± 0.03	0.75 ± 0.02	0.02	0.002	1.08
		Finger lateral range (m)	0.14 ± 0.05	0.16 ± 0.02	0.16	0.002	0.45
		Wrist lateral range (m)	0.07 ± 0.03	0.07 ± 0.03	0.78	0.006	0.02
		Elbow lateral range (m)	0.18 ± 0.03	0.18 ± 0.02	0.46	0.003	0.28
		Shoulder vertical range (m)	0.05 ± 0.03	0.10 ± 0.03	< 0.001*	0.002	1.65
		Hip vertical range (m)	0.09 ± 0.02	0.12 ± 0.01	< 0.001*	0.002	1.90
		Trunk inclination (°)	12.55 ± 2.58	10.42 ± 2.75	0.01*	0.005	0.80
SW2 (Female)	***Push***	**Finger velocity** (m/s)	1.29 ± 0.16	1.28 ± 0.17	0.77	0.050	0.07
		Hip velocity (m/s)	1.32 ± 0.03	1.16 ± 0.03	< 0.001*	0.002	5.23
		Max finger vertical displacement (m)	0.64 ± 0.05	0.68 ± 0.05	0.02	0.002	0.75
		Finger lateral range (m)	0.22 ± 0.09	0.26 ± 0.08	0.03	0.002	0.48
		Wrist lateral range (m)	0.11 ± 0.05	0.11 ± 0.03	0.60	0.004	0.14
		Elbow lateral range (m)	0.21 ± 0.03	0.21 ± 0.04	0.70	0.005	0.15
		Shoulder vertical range (m)	0.08 ± 0.03	0.11 ± 0.02	< 0.001*	0.002	1.36
		Hip vertical range (m)	0.12 ± 0.03	0.15 ± 0.03	0.01	0.003	1.07
		Trunk inclination (°)	14.83 ± 1.99	13.99 ± 1.01	0.23	0.010	0.53
SW3 (Male)	***Push***	**Finger velocity** (m/s)	1.09 ± 0.16	1.53 ± 0.88	< 0.001*	0.003	0.69
		Hip velocity (m/s)	1.39 ± 0.04	1.28 ± 0.04	< 0.001*	0.003	2.74
		Max finger vertical displacement (m)	0.82 ± 0.03	0.84 ± 0.04	0.01*	0.001	0.50
		Finger lateral range (m)	0.27 ± 0.04	0.23 ± 0.03	< 0.001*	0.001	0.89
		Wrist lateral range (m)	0.25 ± 0.02	0.20 ± 0.03	< 0.001*	0.001	1.74
		Elbow lateral range (m)	0.22 ± 0.03	0.19 ± 0.04	< 0.001*	0.001	0.91
		Shoulder vertical range (m)	0.11 ± 0.03	0.15 ± 0.06	< 0.001*	0.003	0.95
		Hip vertical range (m)	0.12 ± 0.01	0.10 ± 0.01	< 0.001*	0.003	1.44
		Trunk inclination (°)	9.98 ± 0.95	9.20 ± 2.04	0.14	0.007	0.49
SW4 (Male)	***Push***	**Finger velocity** (m/s)	1.40 ± 0.11	1.28 ± 0.12	< 0.001*	0.003	1.09
		Hip velocity (m/s)	1.40 ± 0.04	1.18 ± 0.04	< 0.001*	0.003	5.26
		Max finger vertical displacement (m)	0.76 ± 0.04	0.76 ± 0.04	0.90	0.010	0.04
		Finger lateral range (m)	0.14 ± 0.05	0.18 ± 0.07	0.05	0.002	0.64
		Wrist lateral range (m)	0.08 ± 0.03	0.07 ± 0.04	0.44	0.003	0.26
		Elbow lateral range (m)	0.20 ± 0.05	0.22 ± 0.03	0.10	0.003	0.48
		Shoulder vertical range (m)	0.06 ± 0.05	0.06 ± 0.03	0.79	0.013	0.08
		Hip vertical range (m)	0.12 ± 0.02	0.12 ± 0.01	0.01	0.004	0.21
		Trunk inclination (°)	15.98 ± 3.67	14.57 ± 3.53	0.12	0.006	0.39
SW5 (Female)	***Push***	**Finger velocity** (m/s)	1.48 ± 0.12	1.35 ± 0.15	0.01*	0.007	0.93
		Hip velocity (m/s)	1.30 ± 0.05	1.12 ± 0.03	< 0.001*	0.004	4.43
		Max finger vertical displacement (m)	0.69 ± 0.02	0.55 ± 0.25	0.61	0.005	0.79
		Finger lateral range (m)	0.15 ± 0.04	0.24 ± 0.04	< 0.001*	0.001	2.14
		Wrist lateral range (m)	0.07 ± 0.02	0.08 ± 0.02	0.21	0.003	0.61
		Elbow lateral range (m)	0.17 ± 0.04	0.11 ± 0.02	< 0.001*	0.001	1.82
		Shoulder vertical range (m)	0.03 ± 0.03	0.11 ± 0.03	< 0.001*	0.003	2.65
		Hip vertical range (m)	0.17 ± 0.03	0.17 ± 0.03	0.78	0.008	0.14
		Trunk inclination (°)	20.09 ± 0.99	17.38 ± 1.01	< 0.001*	0.005	2.72
SW6 (Male)	***Push***	**Finger velocity** (m/s)	1.24 ± 0.12	1.32 ± 0.16	0.08	0.010	0.58
		Hip velocity (m/s)	1.53 ± 0.07	1.23 ± 0.24	< 0.001*	0.005	1.69
		Max finger vertical displacement (m)	0.71 ± 0.12	0.79 ± 0.02	0.01	0.001	0.89
		Finger lateral range (m)	0.19 ± 0.05	0.19 ± 0.05	0.88	0.008	0.02
		Wrist lateral range (m)	0.11 ± 0.07	0.06 ± 0.04	< 0.001*	0.001	0.94
		Elbow lateral range (m)	0.21 ± 0.08	0.21 ± 0.04	0.97	0.017	0.01
		Shoulder vertical range (m)	0.05 ± 0.03	0.04 ± 0.02	0.38	0.005	0.30
		Hip vertical range (m)	0.13 ± 0.01	0.14 ± 0.01	0.03	0.004	0.80
		Trunk inclination (°)	12.91 ± 3.02	13.17 ± 1.17	0.74	0.017	0.11

Data expressed as mean ± standard deviation, % difference (freestyle vs. *Long Dog* drill swimming), *p* value, Bonferroni-Holm correction *p*-value and effect size.
*indicates a significant difference between freestyle and *Long Dog* drill swimming, using Bonferroni-Holm correction.
$P^{B\text{-}H}$ denotes Bonferroni-Holm correction *p*-value.

6.4.2 Polo drill

The mean temporal race performance variables and relative duration of stroke phases between freestyle and *Polo* drill swimming for each individual participant are presented in Table 6.6. For three participants, *Polo* drill swimming presented a significantly slower SV compared to freestyle and returned large effect sizes. Five participants displayed a significantly shorter average stroke length (SL), a higher SR and shorter total stroke duration when performing the *Polo* drill. Looking at the separate stroke phase durations, *Polo* drill swimming showed a significantly shorter entry and catch duration for four of the participants, three participants displayed a significantly longer pull duration, one participant showed a significantly longer push duration and three participants produced a significantly longer recovery duration.

Table 6.6 Individual-based temporal race performance variables and relative duration of stroke phases between freestyle and the *Polo* drill.

Participant	Variable	Freestyle	*Polo*	P	P^{B-H}	*d*
SW1 (Male)	**Swimming velocity** (m/s)	0.98 ± 0.03	0.94 ± 0.21	0.22	0.006	0.31
	Stroke length (m)	1.94 ± 0.11	1.04 ± 0.06	< 0.001*	0.001	10.03
	Stroke rate (cycles/min)	30.60 ± 0.03	50.00 ± 0.22	< 0.001*	0.001	2.52
	Total duration of SC (s)	1.97 ± 0.10	1.23 ± 0.04	< 0.001*	0.001	9.81
	Entry and catch (% of SC)	47.22 ± 3.21	30.73 ± 6.22	< 0.001*	0.001	3.33
	Pull (% of SC)	15.40 ± 1.42	15.31 ± 2.03	0.91	0.050	0.050
	Push (% of SC)	13.40 ± 3.01	15.77 ± 1.02	0.03	0.003	1.06
	Recovery (% of SC)	23.99 ± 1.75	38.20 ± 4.91	< 0.001*	0.001	3.85
SW2 (Female)	**Swimming velocity** (m/s)	0.91 ± 0.04	0.83 ± 0.04	< 0.001*	0.001	2.14
	Stroke length (m)	1.95 ± 0.05	1.58 ± 0.08	< 0.001*	0.001	5.70
	Stroke rate (cycles/min)	28.20 ± 0.01	31.80 ± 0.03	< 0.001*	0.001	3.05
	Total duration of SC (s)	2.14 ± 0.07	1.90 ± 0.09	< 0.001*	0.001	3.09
	Entry and catch (% of SC)	48.35 ± 1.35	45.21 ± 2.59	< 0.001*	0.001	1.52
	Pull (% of SC)	14.56 ± 1.54	15.38 ± 1.06	0.13	0.005	0.62
	Push (% of SC)	0.30 ± 0.05	0.27 ± 0.05	0.08	0.004	0.63
	Recovery (% of SC)	22.88 ± 1.90	25.00 ± 2.48	0.03	0.003	0.96
SW3 (Male)	**Swimming velocity** (m/s)	0.91 ± 0.10	0.86 ± 0.17	0.35	0.010	0.60
	Stroke length (m)	2.01 ± 0.46	1.70 ± 0.42	0.06	0.004	0.70
	Stroke rate (cycles/min)	28.20 ± 0.10	31.20 ± 0.05	0.20	0.006	0.54
	Total duration of SC (s)	2.19 ± 0.36	1.95 ± 0.18	0.05	0.0033	0.84
	Entry and catch (% of SC)	45.36 ± 10.93	37.11 ± 16.39	0.05	0.004	0.59
	Pull (% of SC)	12.11 ± 3.03	16.10 ± 6.00	0.03	0.003	0.84
	Push (% of SC)	13.40 ± 4.28	13.93 ± 1.15	0.44	0.013	0.67
	Recovery (% of SC)	29.14 ± 5.89	32.85 ± 11.51	0.27	0.008	0.41
SW4 (Male)	**Swimming velocity** (m/s)	0.97 ± 0.04	0.88 ± 0.04	< 0.001*	0.001	2.32
	Stroke length (m)	2.19 ± 0.09	1.49 ± 0.11	< 0.001*	0.001	6.67
	Stroke rate (cycles/min)	26.40 ± 0.01	35.40 ± 0.03	< 0.001*	0.001	7.15
	Total duration of SC (s)	2.27 ± 0.07	1.70 ± 0.08	< 0.001*	0.001	7.82
	Entry and catch (% of SC)	48.43 ± 3.17	35.76 ± 3.28	< 0.001*	0.001	3.93
	Pull (% of SC)	13.19 ± 0.76	15.82 ± 1.77	< 0.001*	0.002	1.93
	Push (% of SC)	12.32 ± 0.71	17.08 ± 3.73	< 0.001*	0.002	1.77
	Recovery (% of SC)	26.06 ± 2.99	31.34 ± 2.93	< 0.001*	0.002	1.79
SW5 (Female)	**Swimming velocity** (m/s)	0.88 ± 0.09	0.79 ± 0.09	0.02	0.003	1.01
	Stroke length (m)	1.79 ± 0.33	1.28 ± 0.14	< 0.001*	0.002	2.02
	Stroke rate (cycles/min)	30.00 ± 0.07	37.20 ± 0.03	< 0.001*	0.002	2.18
	Total duration of SC (s)	2.02 ± 0.23	1.62 ± 0.09	< 0.001*	0.002	2.34
	Entry and catch (% of SC)	41.71 ± 8.41	36.03 ± 7.32	0.08	0.005	0.72
	Pull (% of SC)	13.29 ± 1.17	16.33 ± 3.30	< 0.001*	0.002	1.23
	Push (% of SC)	14.46 ± 3.05	13.74 ± 3.42	0.53	0.017	0.22
	Recovery (% of SC)	30.54 ± 6.82	33.90 ± 8.27	0.25	0.007	0.44
SW6 (Male)	**Swimming velocity** (m/s)	0.93 ± 0.14	0.78 ± 0.10	< 0.001*	0.002	1.24
	Stroke length (m)	1.98 ± 0.56	1.19 ± 0.17	< 0.001*	0.002	1.91
	Stroke rate (cycles/min)	29.40 ± 0.09	40.20 ± 0.13	< 0.001*	0.002	1.62
	Total duration of SC (s)	2.09 ± 0.33	1.54 ± 0.24	< 0.001*	0.002	1.89
	Entry and catch (% of SC)	35.67 ± 14.10	18.52 ± 7.28	< 0.001*	0.002	1.53
	Pull (% of SC)	14.75 ± 2.62	21.79 ± 4.63	< 0.001*	0.002	1.87
	Push (% of SC)	14.45 ± 4.01	14.95 ± 5.03	0.76	0.025	0.11
	Recovery (% of SC)	35.12 ± 9.24	44.74 ± 6.44	< 0.001*	0.002	1.21

Data expressed as mean ± standard deviation, % difference (freestyle vs. *Polo* drill swimming), *p*-value, Bonferroni-Holm correction *p*-value and effect size.
*indicates a significant difference between freestyle and *Polo* drill swimming, using Bonferroni-Holm correction.
SC denotes stroke cycle.
P^{B-H} denotes Bonferroni-Holm correction *p*-value.

Only two participants displayed a significantly larger elbow extension angle at the hand entry instant when *Polo* drill swimming (Table 6.7). At the catch instant, four participants showed significant differences between freestyle and the *Polo* drill with three producing greater elbow flexion when *Polo* drill swimming and one producing less elbow flexion compared to freestyle. Three participants displayed significant differences at the shoulder instant when performing the *Polo* drill with one showing greater elbow flexion and two showing less elbow flexion. Further, only one participant displayed a significantly greater elbow extension at the release instant when *Polo* drill swimming.

Table 6.7 Individual-based mean elbow flexion/extension angle at specified instants throughout the underwater stroke phase between freestyle and the *Polo* drill.

Participant	Variable (°)	Freestyle	*Polo*	P	P^{B-H}	*d*
SW1 (Male)	**Elbow angle at entry**	103.7 ± 32.0	118.2 ± 39.9	0.34	0.008	0.40
	Elbow angle at catch	154.4 ± 8.8	112.0 ± 29.8	< 0.001*	0.002	1.93
	Elbow angle at shoulder	108.0 ± 5.2	99.6 ± 19.0	0.52	0.025	0.60
	Elbow angle at release	142.1 ± 10.9	131.2 ± 19.8	0.11	0.004	0.68
SW2 (Female)	**Elbow angle at entry**	112.7 ± 13.5	105.6 ± 46.0	0.67	0.050	0.21
	Elbow angle at catch	146.1 ± 19.9	153.3 ± 5.9	0.25	0.006	0.49
	Elbow angle at shoulder	94.6 ± 11.2	101.7 ± 11.9	0.27	0.006	0.62
	Elbow angle at release	147.0 ± 11.2	140.9 ± 13.1	0.33	0.007	0.50
SW3 (Male)	**Elbow angle at entry**	133.3 ± 2.2	140.2 ± 15.8	0.42	0.013	0.29
	Elbow angle at catch	143.4 ± 2.2	150.9 ± 5.2	< 0.001*	0.002	1.87
	Elbow angle at shoulder	122.1 ± 8.4	110.2 ± 10.8	< 0.001*	0.002	1.23
	Elbow angle at release	139.1 ± 11.4	135.2 ± 10.8	0.34	0.010	0.35
SW4 (Male)	**Elbow angle at entry**	114.5 ± 25.9	164.1 ± 6.8	< 0.001*	0.002	2.62
	Elbow angle at catch	152.0 ± 6.3	148.6 ± 5.1	0.07	0.004	0.60
	Elbow angle at shoulder	113.8 ± 2.9	121.1 ± 6.6	< 0.001*	0.003	1.42
	Elbow angle at release	128.8 ± 6.7	136.3 ± 15.0	0.17	0.005	0.64
SW5 (Female)	**Elbow angle at entry**	132.6 ± 18.4	153.3 ± 17.3	0.01*	0.003	1.16
	Elbow angle at catch	152.6 ± 7.3	149.1 ± 7.2	< 0.001*	0.003	1.16
	Elbow angle at shoulder	108.7 ± 2.4	119.5 ± 4.5	< 0.001*	0.003	2.98
	Elbow angle at release	108.8 ± 26.0	129.0 ± 19.5	0.03*	00003	0.88
SW6 (Male)	**Elbow angle at entry**	120.3 ± 52.6	147.4 ± 11.3	0.11	0.004	0.71
	Elbow angle at catch	155.1 ± 7.4	141.4 ± 13.5	< 0.001*	0.003	1.26
	Elbow angle at shoulder	102.5 ± 6.2	105.8 ± 33.3	0.42	0.017	0.14
	Elbow angle at release	131.7 ± 18.8	142.5 ± 19.9	0.11	0.005	0.56

Data expressed as mean ± standard deviation, % difference (freestyle vs. *Polo* drill swimming), *p*-value, Bonferroni-Holm correction *p*-value and effect size.
*indicates a significant difference between freestyle and *Polo* drill swimming, using Bonferroni-Holm correction.
P^{B-H} denotes Bonferroni-Holm correction *p*-value.

Figure 6.4 and 6.5 illustrates the frontal view of the lateral and vertical finger displacement between freestyle and *Polo* drill swimming for each individual swimmer on the right- and left-handed stroke cycles, respectively. Topological observations of the stroke signatures demonstrate the presence of intra-individual similarities in finger position and displacement between freestyle and *Polo* drill swimming. Further, the figures demonstrate the presence of inter-individual differences of the finger's trajectory.

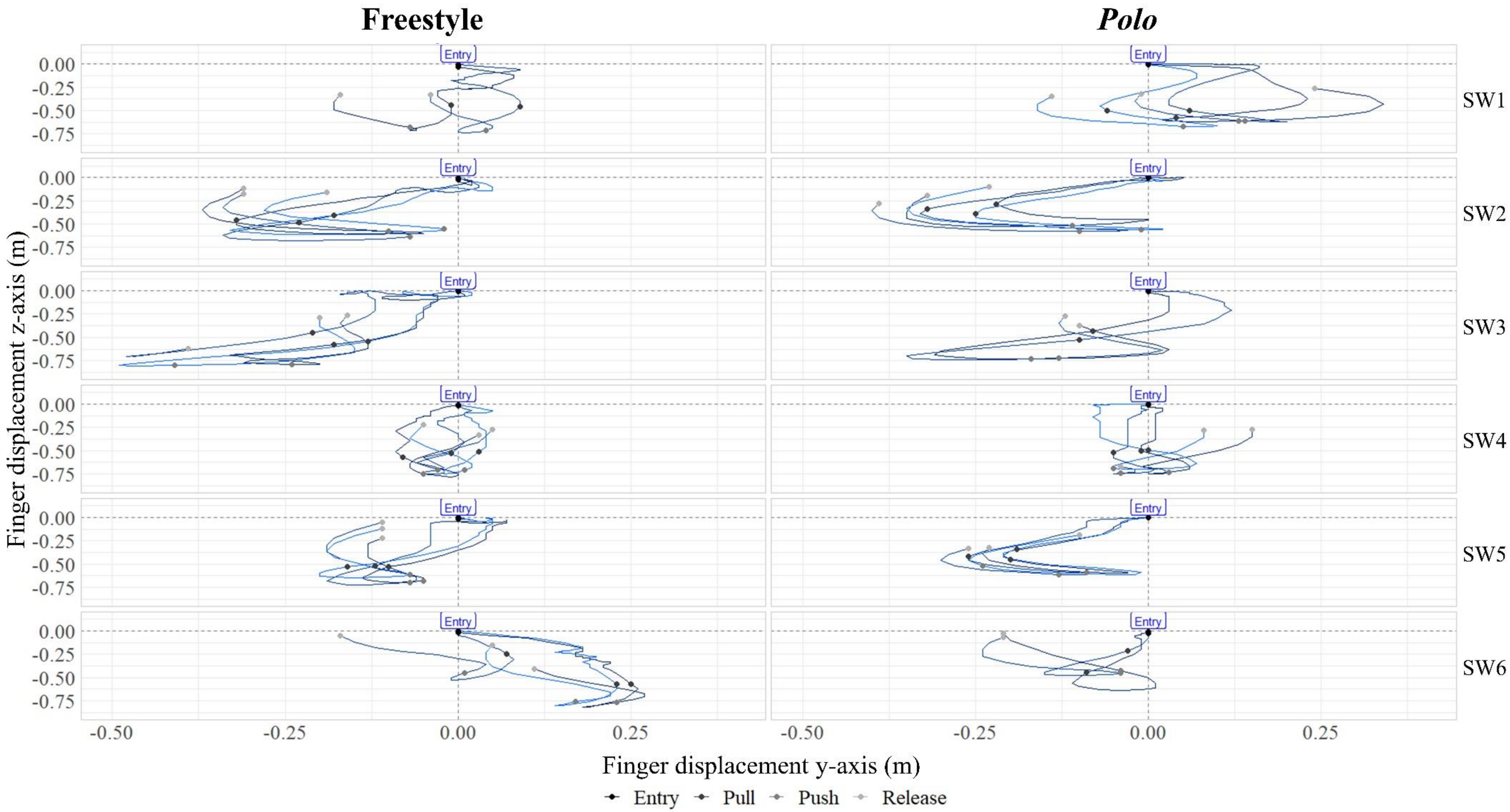


Figure 6.4 Frontal view of the right finger's trajectory for each individual participant during freestyle and *Polo* drill swimming. Lateral finger displacement standardised to start at zero.

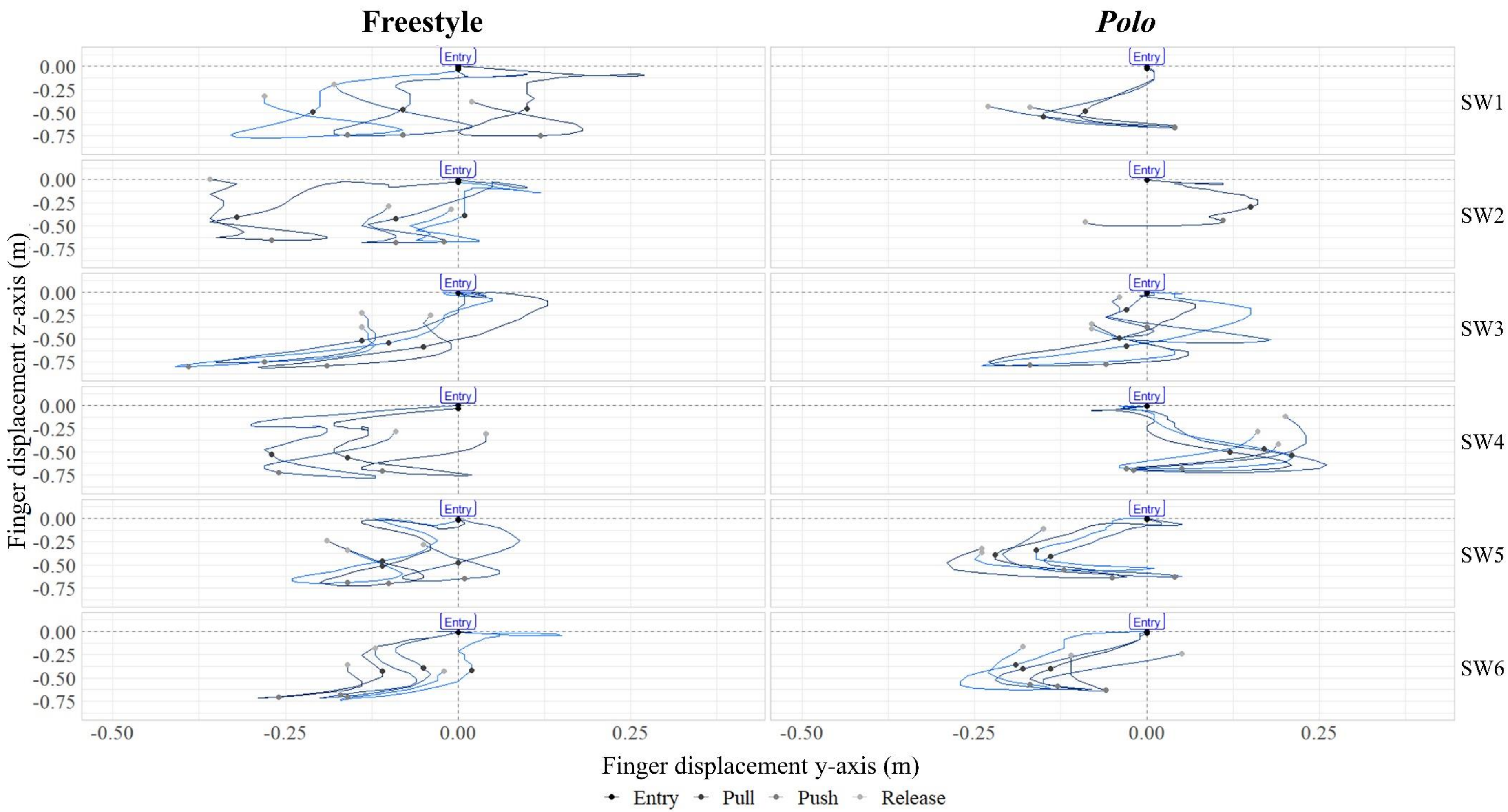


Figure 6.5 Frontal view of the left finger's trajectory for each individual participant during freestyle and *Polo* drill swimming. Lateral finger displacement standardised to start at zero.

6.4.2.1 Entry and catch phase

Three participants presented significantly higher average finger velocity values within the entry and catch phase when *Polo* drill swimming by 0.62, 0.15 and 0.27 m/s, respectively (Table 6.8). Two participants showed significantly different hip velocity average values with one participant producing a greater hip velocity and the other producing a lower average hip velocity value. Five participants produced a significantly shallower maximum finger vertical displacement when *Polo* drill swimming and returned large effect sizes. One participant displayed a significantly greater finger lateral range when performing the *Polo* drill and three participants showed significantly larger elbow lateral range values. Additionally, two participants produced significantly different wrist lateral range values with one producing a smaller range and the other producing a larger range. Only one participant displayed a significantly different shoulder vertical range between freestyle and *Polo* drill swimming, returning a large effect size. Further, the hip vertical range was significantly lower when performing the *Polo* drill for three participants.

Table 6.8 Kinematic parameters within the entry and catch phase of the stroke between freestyle and the *Polo* drill.

Participant		Variable	Freestyle	*Polo*	P	P^{B-H}	*d*
SW1 (Male)	***Entry and Catch***	**Finger velocity** (m/s)	1.35 ± 0.12	0.73 ± 0.31	< 0.001*	0.001	2.64
		Hip velocity (m/s)	1.30 ± 0.03	1.39 ± 0.03	< 0.001*	0.001	3.52
		Max finger vertical displacement (m)	0.46 ± 0.02	0.52 ± 0.04	< 0.001*	0.004	1.98
		Finger lateral range (m)	0.17 ± 0.06	0.15 ± 0.04	0.68	0.025	0.20
		Wrist lateral range (m)	0.12 ± 0.07	0.13 ± 0.04	0.62	0.017	0.14
		Elbow lateral range (m)	0.09 ± 0.03	0.13 ± 0.04	< 0.001*	0.005	1.03
		Shoulder vertical range (m)	0.08 ± 0.03	0.04 ± 0.02	0.01	0.003	1.47
		Hip vertical range (m)	0.25 ± 0.04	0.06 ± 0.01	< 0.001*	0.001	5.82
		Trunk inclination (°)	16.78 ± 1.48	23.18 ± 2.30	< 0.001*	0.002	3.31
SW2 (Female)	***Entry and Catch***	**Finger velocity** (m/s)	1.36 ± 0.08	1.21 ± 0.01	< 0.001*	0.002	2.75
		Hip velocity (m/s)	1.17 ± 0.03	1.12 ± 0.03	< 0.001*	0.002	2.00
		Max finger vertical displacement (m)	0.44 ± 0.03	0.33 ± 0.04	< 0.001*	0.004	2.90
		Finger lateral range (m)	0.26 ± 0.07	0.25 ± 0.06	0.64	0.025	0.15
		Wrist lateral range (m)	0.22 ± 0.06	0.19 ± 0.05	0.16	0.013	0.50
		Elbow lateral range (m)	0.10 ± 0.02	0.13 ± 0.03	0.01*	0.006	1.04
		Shoulder vertical range (m)	0.06 ± 0.04	0.02 ±0.01	0.01	0.003	1.4
		Hip vertical range (m)	0.23 ± 0.02	0.16 ± 0.03	< 0.001*	0.002	2.98
		Trunk inclination (°)	22.74 ± 9.24	27.44 ± 0.75	0.20	0.03	0.72
SW3 (Male)	***Entry and Catch***	**Finger velocity** (m/s)	1.28 ± 0.27	1.12 ± 0.34	0.11	0.005	0.52
		Hip velocity (m/s)	1.26 ± 0.04	1.27 ± 0.08	0.41	0.013	0.16
		Max finger vertical displacement (m)	0.54 ± 0.04	0.44 ± 0.14	0.03	0.008	0.91
		Finger lateral range (m)	0.17 ± 0.02	0.13 ± 0.07	0.04	0.010	0.78
		Wrist lateral range (m)	0.18 ± 0.05	0.12 ± 0.05	< 0.001*	0.004	1.17
		Elbow lateral range (m)	0.14 ± 0.02	0.11 ± 0.04	0.02	0.007	0.89
		Shoulder vertical range (m)	0.15 ± 0.01	0.07 ± 0.02	< 0.001*	0.002	4.49
		Hip vertical range (m)	0.25 ± 0.09	0.19 ± 0.09	0.05	0.005	0.66
		Trunk inclination (°)	19.08 ± 1.93	23.19 ± 4.58	< 0.001*	0.003	1.17
SW4 (Male)	***Entry and Catch***	**Finger velocity** (m/s)	1.45 ± 0.08	1.18 ± 0.17	< 0.001*	0.002	2.00
		Hip velocity (m/s)	1.28 ± 0.02	1.27 ± 0.10	0.38	0.010	0.11
		Max finger vertical displacement (m)	0.54 ± 0.02	0.50 ± 0.02	< 0.001*	0.004	1.67
		Finger lateral range (m)	0.13 ± 0.10	0.10 ± 0.10	0.02	0.006	0.33
		Wrist lateral range (m)	0.11 ± 0.07	0.12 ± 0.11	0.73	0.050	0.06
		Elbow lateral range (m)	0.08 ± 0.03	0.10 ± 0.04	0.06	0.013	0.58
		Shoulder vertical range (m)	0.08 ± 0.02	0.05 ± 0.03	0.01	0.003	0.94
		Hip vertical range (m)	0.25 ± 0.02	0.15 ± 0.04	< 0.001*	0.002	3.45
		Trunk inclination (°)	14.21 ± 2.47	20.74 ± 2.62	< 0.001*	0.003	2.56
SW5 (Female)	***Entry and Catch***	**Finger velocity** (m/s)	1.25 ± 0.20	1.15 ± 0.13	0.1	0.004	0.61
		Hip velocity (m/s)	1.25 ± 0.03	1.21 ± 0.07	0.01	0.003	0.85
		Max finger vertical displacement (m)	0.51 ± 0.03	0.40 ± 0.04	< 0.001*	0.004	3.39
		Finger lateral range (m)	0.15 ± 0.04	0.21 ± 0.03	< 0.001*	0.005	1.76
		Wrist lateral range (m)	0.14 ± 0.03	0.17 ± 0.02	< 0.001*	0.005	1.28
		Elbow lateral range (m)	0.11 ± 0.03	0.17 ± 0.04	< 0.001*	0.006	1.65
		Shoulder vertical range (m)	0.05 ± 0.03	0.03 ± 0.02	0.01	0.003	0.98
		Hip vertical range (m)	0.16 ± 0.07	0.10 ± 0.03	0.06	0.006	1.09
		Trunk inclination (°)	21.74 ± 1.06	27.19 ± 1.68	< 0.001*	0.004	3.88
SW6 (Male)	***Entry and Catch***	**Finger velocity** (m/s)	1.30 ± 0.30	0.98 ± 0.30	0.01	0.004	1.07
		Hip velocity (m/s)	1.37 ± 0.06	1.37 ± 0.10	0.91	0.025	0.04
		Max finger vertical displacement (m)	0.43 ± 0.10	0.36 ± 0.08	0.01*	0.006	0.76
		Finger lateral range (m)	0.15 ± 0.07	0.13 ± 0.06	0.41	0.017	0.36
		Wrist lateral range (m)	0.12 ± 0.08	0.14 ± 0.09	0.50	0.025	0.50
		Elbow lateral range (m)	0.12 ± 0.05	0.15 ± 0.05	0.17	0.010	0.49
		Shoulder vertical range (m)	0.08 ± 0.04	0.03 ± 0.03	< 0.001*	0.002	1.21
		Hip vertical range (m)	0.19 ± 0.11	0.05 ± 0.02	0.01	0.004	1.65
		Trunk inclination (°)	18.38 ± 6.25	19.67 ± 1.81	0.30	0.05	0.28

Data expressed as mean ± standard deviation, % difference (freestyle vs. *Polo* drill swimming), *p*-value, Bonferroni-Holm correction *p*-value and effect size.
*indicates a significant difference between freestyle and *Polo* drill swimming, using Bonferroni-Holm correction.
P^{B-H} denotes Bonferroni-Holm correction *p*-value.

6.4.2.2 Pull phase

In the pull phase, five participants displayed significantly higher finger velocity values when performing the *Polo* drill (Table 6.9). Additionally, two participants displayed significant differences in hip velocity between freestyle and *Polo* drill with one participant showing a higher hip velocity and the other presenting a lower hip velocity. All six participants produced shallower maximum finger vertical displacement values and smaller elbow lateral range values when performing the *Polo* drill, returning large effect sizes. Two participants displayed significantly greater finger lateral range values when performing the *Polo* drill and one participant showed a significantly smaller wrist lateral range. Further, four participants displayed a significantly smaller shoulder vertical range when performing the *Polo* drill. The hip vertical range was also significantly smaller for five participants when *Polo* drill swimming, returning large effect sizes.

Table 6.9 Kinematic parameters within the pull phase of the stroke between freestyle and the *Polo* drill.

Participant		Variable	Freestyle	*Polo*	P	$P^{B\text{-}H}$	*d*
SW1 (Male)	***Pull***	**Finger velocity** (m/s)	1.16 ± 0.10	1.46 ± 0.29	< 0.001*	0.001	1.36
		Hip velocity (m/s)	1.19 ± 0.05	1.34 ± 0.02	< 0.001*	0.001	3.78
		Max finger vertical displacement (m)	0.74 ± 0.02	0.65 ± 0.02	< 0.001*	0.005	4.60
		Finger lateral range (m)	0.11 ± 0.04	0.15 ± 0.03	< 0.001*	0.006	1.25
		Wrist lateral range (m)	0.08 ± 0.02	0.09 ± 0.03	0.85	0.050	0.09
		Elbow lateral range (m)	0.15 ± 0.03	0.04 ± 0.05	< 0.001*	0.006	2.73
		Shoulder vertical range (m)	0.07 ± 0.04	0.03 ± 0.02	< 0.001*	0.001	1.59
		Hip vertical range (m)	0.17 ± 0.01	0.07 ± 0.01	< 0.001*	0.001	12.51
		Trunk inclination (°)	13.57 ± 3.10	21.27 ± 3.63	< 0.001*	0.002	2.28
SW2 (Female)	***Pull***	**Finger velocity** (m/s)	0.72 ± 0.14	1.02 ± 0.09	< 0.001*	0.002	2..64
		Hip velocity (m/s)	1.13 ± 0.04	1.01 ± 0.11	0.01	0.003	1.45
		Max finger vertical displacement (m)	0.64 ± 0.03	0.53 ± 0.06	< 0.001*	0.005	2.52
		Finger lateral range (m)	0.23 ± 0.09	0.21 ± 0.10	0.20	0.017	0.16
		Wrist lateral range (m)	0.12 ± 0.01	0.09 ± 0.04	0.07	0.010	0.89
		Elbow lateral range (m)	0.14 ± 0.02	0.06 ±0.03	< 0.001*	0.005	3.14
		Shoulder vertical range (m)	0.06 ± 0.02	0.03 ± 0.00	< 0.001*	0.002	1.73
		Hip vertical range (m)	0.12 ± 0.03	0.09 ± 0.03	< 0.001*	0.002	1.09
		Trunk inclination (°)	16.51 ± 6.13	24.10 ± 2.37	< 0.001*	0.003	1.63
SW3 (Male)	***Pull***	**Finger velocity** (m/s)	1.24 ± 0.11	1.21 ± 0.05	0.82	0.017	0.33
		Hip velocity (m/s)	1.19 ± 0.02	1.18 ± 0.05	0.25	0.008	0.38
		Max finger vertical displacement (m)	0.79 ± 0.03	0.72 ± 0.10	0.01*	0.005	1.02
		Finger lateral range (m)	0.24 ± 0.10	0.21 ± 0.03	0.12	0.025	0.41
		Wrist lateral range (m)	0.19 ± 0.07	0.15 ± 0.02	0.7	0.050	0.75
		Elbow lateral range (m)	0.16 ± 0.02	0.14 ± 0.02	0.01*	0.005	1.18
		Shoulder vertical range (m)	0.07 ± 0.02	0.05 ± 0.01	0.02	0.004	1.07
		Hip vertical range (m)	0.12 ± 0.01	0.13 ± 0.03	0.46	0.013	0.30
		Trunk inclination (°)	5.76 ± 2.11	17.94 ± 5.48	< 0.001*	0.003	2.93
SW4 (Male)	***Pull***	**Finger velocity** (m/s)	1.16 ± 0.05	1.34 ± 0.14	< 0.001*	0.002	1.73
		Hip velocity (m/s)	1.26 ± 0.03	1.24 ± 0.05	0.21	0.007	0.51
		Max finger vertical displacement (m)	0.76 ± 0.01	0.72 ± 0.03	< 0.001*	0.005	2.00
		Finger lateral range (m)	0.09 ± 0.07	0.13 ± 0.09	0.03	0.007	0.45
		Wrist lateral range (m)	0.08 ± 0.03	0.06 ± 0.01	0.05	0.008	0.77
		Elbow lateral range (m)	0.13 ± 0.01	0.09 ± 0.02	< 0.001*	0.005	2.81
		Shoulder vertical range (m)	0.09 ± 0.01	0.04 ± 0.02	< 0.001*	0.002	3.23
		Hip vertical range (m)	0.15 ± 0.01	0.10 ± 0.02	< 0.001*	0.002	3.02
		Trunk inclination (°)	14.26 ± 2.62	20.15 ± 2.21	< 0.001*	0.004	2.43
SW5 (Female)	***Pull***	**Finger velocity** (m/s)	1.08 ± 0.06	1.34 ± 0.14	< 0.001*	0.002	2.39
		Hip velocity (m/s)	1.21 ± 0.03	1.15 ± 0.06	< 0.001*	0.002	1.37
		Max finger vertical displacement (m)	0.69 ± 0.03	0.61 ± 0.03	< 0.001*	0.006	3.10
		Finger lateral range (m)	0.11 ± 0.02	0.19 ± 0.02	< 0.001*	0.007	3.43
		Wrist lateral range (m)	0.08 ± 0.03	0.07 ± 0.02	0.62	0.050	0.20
		Elbow lateral range (m)	0.12 ± 0.02	0.05 ± 0.03	< 0.001*	0.008	2.43
		Shoulder vertical range (m)	0.05 ± 0.02	0.03 ± 0.02	< 0.001*	0.002	1.20
		Hip vertical range (m)	0.09 ± 0.01	0.07 ± 0.02	< 0.001*	0.002	1.34
		Trunk inclination (°)	17.53 ± 1.65	26.11 ± 1.84	< 0.001*	0.005	4.90
SW6 (Male)	***Pull***	**Finger velocity** (m/s)	1.16 ± 0.07	1.54 ± 0.02	< 0.001*	0.003	3.09
		Hip velocity (m/s)	1.35 ± 0.04	1.38 ± 0.08	0.19	0.006	0.55
		Max finger vertical displacement (m)	0.72 ± 0.09	0.60 ± 0.06	0.01*	0.006	1.55
		Finger lateral range (m)	0.14 ± 0.05	0.12 ± 0.01	0.34	0.013	0.34
		Wrist lateral range (m)	0.14 ± 0.06	0.09 ± 0.04	0.01*	0.007	0.94
		Elbow lateral range (m)	0.21 ± 0.02	0.13 ± 0.05	< 0.001*	0.004	2.22
		Shoulder vertical range (m)	0.05 ± 0.01	0.05 ± 0.03	0.33	0.013	0.32
		Hip vertical range (m)	0.16 ± 0.01	0.14 ± 0.01	< 0.001*	0.002	2.60
		Trunk inclination (°)	14.93 ± 6.57	22.53 ± 2.56	< 0.001*	0.006	1.53

Data expressed as mean ± standard deviation, % difference (freestyle vs. *Polo* drill swimming), *p*-value, Bonferroni-Holm correction *p*-value and effect size.
*indicates a significant difference between freestyle and *Polo* drill swimming, using Bonferroni-Holm correction.
$P^{B\text{-}H}$ denotes Bonferroni-Holm correction *p*-value.

6.4.2.3 Push phase

The push phase displayed a greater finger velocity for four participants and a lower hip velocity for two participants when performing the *Polo* drill (Table 6.10). Five participants showed a shallower maximum finger vertical displacement when swimming the *Polo* drill compared to freestyle. Two participants presented greater finger lateral range values when performing the *Polo* drill, returning moderate to large effect sizes. Four participants showed significantly different wrist lateral range values with two producing a smaller range when *Polo* drill swimming and two producing a larger range. *Polo* drill swimming also presented significantly smaller elbow lateral range values for two participants compared to freestyle. One participant showed a significantly larger shoulder vertical range when *Polo* drill swimming. Conversely, the hip vertical range was significantly smaller for two participants when performing the *Polo* drill while the remaining four participants displayed no significant differences. Only one participant displayed no significant difference in trunk inclination between the freestyle and *Polo* drill.

Table 6.10 Kinematic parameters within the push phase of the stroke between freestyle and the *Polo* drill.

Participant		Variable	Freestyle	*Polo*	P	$P^{B\text{-}H}$	*d*
SW1 (Male)	***Push***	**Finger velocity** (m/s)	1.47 ± 0.35	1.89 ± 0.10	< 0.001*	0.001	1.63
		Hip velocity (m/s)	1.38 ± 0.04	1.36 ± 0.10	0.98	0.050	0.30
		Max finger vertical displacement (m)	0.72 ± 0.03	0.64 ± 0.02	< 0.001*	0.007	2.91
		Finger lateral range (m)	0.14 ± 0.05	0.22 ± 0.04	< 0.001*	0.008	1.71
		Wrist lateral range (m)	0.06 ± 0.04	0.09 ± 0.06	0.02	0.013	0.71
		Elbow lateral range (m)	0.15 ± 0.03	0.07 ± 0.04	< 0.001*	0.010	2.32
		Shoulder vertical range (m)	0.07 ± 0.04	0.05 ± 0.04	0.47	0.025	0.38
		Hip vertical range (m)	0.10 ± 0.01	0.08 ± 0.03	0.02	0.004	10.8
		Trunk inclination (°)	14.04 ± 4.59	25.28 ± 4.20	< 0.001*	0.002	2.56
SW2 (Female)	***Push***	**Finger velocity** (m/s)	1.37 ± 0.20	1.66 ± 0.23	< 0.001*	0.002	1.31
		Hip velocity (m/s)	1.28 ± 0.05	1.19 ± 0.13	0.14	0.006	0.91
		Max finger vertical displacement (m)	0.61 ± 0.05	0.54 ± 0.03	0.01*	0.006	1.62
		Finger lateral range (m)	0.20 ± 0.11	0.27 ± 0.05	0.02	0.010	0.79
		Wrist lateral range (m)	0.06 ± 0.03	0.18 ±0.12	0.01*	0.007	1.39
		Elbow lateral range (m)	0.19 ± 0.07	0.20 ± 0.11	0.97	0.050	0.01
		Shoulder vertical range (m)	0.05 ± 0.03	0.06 ± 0.04	0.05	0.005	0.50
		Hip vertical range (m)	0.10 ± 0.03	0.09 ± 0.02	0.28	0.010	0.41
		Trunk inclination (°)	20.86 ± 8.31	30.84 ± 5.29	0.02	0.01	1.43
SW3 (Male)	***Push***	**Finger velocity** (m/s)	1.09 ± 0.18	1.51 ± 0.15	< 0.001*	0.002	2.49
		Hip velocity (m/s)	1.30 ± 0.34	1.33 ± 0.05	0.12	0.005	0.13
		Max finger vertical displacement (m)	0.78 ± 0.02	0.67 ± 0.16	0.01*	0.006	0.93
		Finger lateral range (m)	0.19 ± 0.06	0.14 ± 0.07	0.08	0.017	0.74
		Wrist lateral range (m)	0.21 ± 0.05	0.14 ± 0.03	< 0.001*	0.005	1.80
		Elbow lateral range (m)	0.23 ± 0.07	0.17 ± 0.03	0.04	0.013	1.12
		Shoulder vertical range (m)	0.07 ± 0.04	0.03 ± 0.02	0.01	0.003	1.53
		Hip vertical range (m)	0.11 ± 0.01	0.09 ± 0.03	0.03	0.004	0.87
		Trunk inclination (°)	10.67 ± 3.73	22.08 ± 3.60	< 0.001*	0.003	3.11
SW4 (Male)	***Push***	**Finger velocity** (m/s)	1.49 ± 0.15	1.74 ± 0.33	0.02	0.004	0.96
		Hip velocity (m/s)	1.43 ± 0.03	1.32 ± 0.08	< 0.001*	0.002	1.81
		Max finger vertical displacement (m)	0.72 ± 0.02	0.71 ± 0.02	0.08	0.017	0.64
		Finger lateral range (m)	0.12 ± 0.06	0.16 ± 0.06	< 0.001*	0.006	0.57
		Wrist lateral range (m)	0.03 ± 0.02	0.08 ± 0.04	< 0.001*	0.006	1.91
		Elbow lateral range (m)	0.12 ± 0.04	0.13 ± 0.04	0.67	0.025	0.20
		Shoulder vertical range (m)	0.05 ± 0.03	0.05 ± 0.03	0.77	0.050	0.11
		Hip vertical range (m)	0.10 ± 0.01	0.12 ± 0.04	0.13	0.008	0.67
		Trunk inclination (°)	18.14 ± 3.47	23.13 ± 3.51	0.01*	0.01	1.43
SW5 (Female)	***Push***	**Finger velocity** (m/s)	1.38 ± 0.25	1.72 ± 0.37	0.01	0.003	1.06
		Hip velocity (m/s)	1.33 ± 0.05	1.21 ± 0.09	< 0.001*	0.002	1.62
		Max finger vertical displacement (m)	0.67 ± 0.03	0.59 ± 0.04	< 0.001*	0.010	2.05
		Finger lateral range (m)	0.16 ± 0.13	0.23 ± 0.06	0.13	0.13	0.59
		Wrist lateral range (m)	0.14 ± 0.12	0.10 ± 0.07	0.33	0.33	0.39
		Elbow lateral range (m)	0.18 ± 0.11	0.09 ± 0.03	0.02	0.013	1.09
		Shoulder vertical range (m)	0.04 ± 0.03	0.05 ± 0.01	0.11	0.007	0.50
		Hip vertical range (m)	0.15 ± 0.02	0.10 ± 0.02	< 0.001*	0.002	2.13
		Trunk inclination (°)	21.84 ± 2.40	29.89 ± 4.62	< 0.001*	0.005	2.19
SW6 (Male)	***Push***	**Finger velocity** (m/s)	1.23 ± 0.11	1.63 ± 0.14	< 0.001*	0.003	3.14
		Hip velocity (m/s)	1.64 ± 0.12	1.47 ± 0.03	< 0.001*	0.003	1.98
		Max finger vertical displacement (m)	0.68 ± 0.10	0.53 ± 0.08	< 0.001*	0.005	1.64
		Finger lateral range (m)	0.15 ± 0.04	0.14 ± 0.07	0.49	0.14	0.19
		Wrist lateral range (m)	0.14 ± 0.07	0.03 ± 0.03	< 0.001*	0.005	1.96
		Elbow lateral range (m)	0.24 ± 0.06	0.19 ± 0.06	0.01*	0.008	1.00
		Shoulder vertical range (m)	0.05 ± 0.04	0.09 ± 0.03	< 0.001*	0.002	1.16
		Hip vertical range (m)	0.12 ± 0.01	0.08 ± 0.02	< 0.001*	0.003	1.99
		Trunk inclination (°)	14.86 ± 4.83	29.87 ± 5.76	< 0.001*	0.007	2.82

Data expressed as mean ± standard deviation, % difference (freestyle vs. *Polo* drill swimming), *p*-value, Bonferroni-Holm correction *p*-value and effect size.
*indicates a significant difference between freestyle and *Polo* drill swimming, using Bonferroni-Holm correction.
$P^{B\text{-}H}$ denotes Bonferroni-Holm correction *p*-value.

6.5 Discussion

The purpose of this study was to investigate if individuals displayed different movement characteristics between freestyle and drill swimming. The *Long Dog* and *Polo* drill were selected as the vehicle for this assessment in order to extent the findings presented in Study Two (Chapter 5). This study was unique because an individual-based analysis approach was used to measure the key movement and performance characteristics of freestyle swimming drills.

6.5.1 Long Dog drill

6.5.1.1 Pull phase

Five participants showed no significant differences in the relative duration of the pull phase between freestyle and *Long Dog* drill swimming. However, participant SW4 displayed a significantly shorter relative pull phase duration and a larger finger lateral range of motion when performing the *Long Dog* drill. Anecdotal observations of the *Long Dog* drill have suggested that the breathing pattern may influence a greater pull path width. Studies have also revealed that a greater lateral displacement of the hand might be attributed to either a different amount of shoulder roll between experimental conditions or a slower average SV (Guignard, Rouard, Chollet, Hart, et al., 2017; Psycharakis & Sanders, 2010; Sanders et al., 2017). Participant SW4 also showed a significantly slower SV when performing the *Long Dog* drill while differences in shoulder and hip displacement were not significant. Further, participant SW4 displayed no significant differences in trunk inclination to freestyle when performing the *Long Dog* drill. This indicated that for participant SW4, the *Long Dog* drill may help maintain a similar body rotation and trunk inclination to freestyle. However, as participant SW4 was a sprint-distance swimmer, the larger finger lateral range of motion and finger trajectories does not appear to represent the hand pull path typically adopted in competition (Guignard, Rouard, Chollet, Hart, et al., 2017; Sanders et al., 2017). This reiterated what some swimming coaches already understand in regards to drill prescription. That being, although the drill may focus on maintaining a similar body rotation and trunk inclination to freestyle, it may negatively affect another aspect(s) of the stroke for particular swimmers (Brackley, Barris, et al., 2020). Consequently, the overuse of drills can create additional technique imbalances detrimental to efficient and fast performance in competition.

Participant SW1 displayed no significant differences in the finger pull path to freestyle yet a significantly smaller wrist and elbow lateral range of motion when *Long Dog* drill swimming. This suggests that for another sprint-distance swimmer, the *Long Dog* drill may produce upper-limb movements representative to sprint-distance swimming in competition (Guignard, Rouard, Chollet, Hart, et al., 2017; Sanders et al., 2017). Further, while the *Long Dog* many represent body rotation, trunk inclination and the finger path within the pull phase of slow-paced freestyle for participant SW1, future research is required to investigate if and how the *Long Dog* drill alters freestyle technique in competition performance (race-paced freestyle).

Participants SW2 and SW5 presented no significant differences in upper-limb movement between freestyle and *Long Dog* drill swimming. Further, participants SW2 and SW5 displayed no significant differences in shoulder and hip vertical range values. This suggests that the *Long Dog* drill may represents the hand path and body rotation displayed in slow-paced freestyle. While the group-based analysis revealed that the finger velocity was significantly slower when performing the *Long Dog* drill (see Chapter 5), finger velocity was significantly higher for participant SW2. Studies have suggested that a higher hand velocity within the propulsive phase of the stroke may relate to higher propulsive forces (Chollet et al., 2000; Lerda & Cardelli, 2003). Further work is required to confirm whether this higher hand velocity propulsive hand trajectory transfers to competition swimming.

The long-distance swimmers, participants SW3 and SW6, showed a significantly deeper maximal vertical displacement of the finger when performing the *Long Dog* drill. This may have been associated with the significantly greater elbow flexion at the catch instant. Studies have shown, however, that the elbow is less extended at the catch instant for long-distance freestyle swimmers where an ‘S’-shaped pull path is typically adopted (Nakashima et al., 2012; Payton, Bartlett, Baltzopoulos, & Coombs, 1999). Hence, the removal of the above-water recovery phase when *Long Dog* drill swimming presents upper-limb modifications that may not be representative to the pull depth and elbow flexion typically observed in long-distance freestyle swimmers. As one of the intentions of the *Long Dog* drill is to improve the hand position within the pull phase of the stroke, the abovementioned results suggests that the prescription of specific practice tasks requires consideration of the swimmer’s distance specialisation. Rather than prescribing the *Long Dog* drill, coaches may want to consider the constraints-led approach, underpinned by RLD (Pinder & Renshaw, 2019; Seifert et al., 2013). Specifically, the manipulation of constraints may benefit the improvement of specific aspects of the freestyle stroke rather than the prescription of drills that decompose the skill into smaller components. For example, the use of hand paddles or fins increases the upper-limb propulsive surfaces in order to help the swimmer improve the hand position and pull trajectory without decomposing the freestyle technique skill (Seifert et al., 2013).

6.5.1.2 Push phase

In the push phase, four participants showed no significant differences in finger lateral range values between freestyle and the *Long Dog* drill. Conversely, participant SW3 showed significantly smaller upper-limb lateral range of motion values when performing the *Long Dog* drill. Further, the relative push phase duration was significantly shorter and the finger velocity displayed a higher average value. This indicated that the shorter push duration was compensated by a higher finger velocity. However, the stroke signatures displayed similar underwater finger trajectories between freestyle and *Long Dog* drill Figure 6.2 and 6.3, p. 183 - 184). The findings align with those of Sanders et al. (2019) that the consistency of the hand path is a result of effective compensation through functional variability of segmental and joint contributions across other variables.

In contrast to participant SW3, participant SW5 displayed a significantly greater finger lateral range of motion and less elbow lateral range of motion within the push phase when swimming the *Long Dog* drill. However, the trunk showed significantly less inclination which suggests that the swimmer continued to maintain a streamline body positing when performing the *Long Dog* drill. As participant SW5 was a middle-distance swimmer, the greater finger lateral range of motion may also support the ‘S’-shaped pull path typically adopted by middle- to long-distance swimmers in competition (Sanders et al., 2017). Contrarily, this upper-limb modification was not displayed in the other middle-distance swimmer, participant SW2. These findings reiterate the need for individual-specific assessment and prescription of drills as the *Long Dog* drill influenced various stroke parameters differently depending on the swimmer.

6.5.2 Polo drill

6.5.2.1 Entry and catch phase

Inspection of the frontal representative views of the lateral and vertical finger displacement for each individual participant (Figure 6.4 and 6.5, p. 192 - 193) revealed both topological similarities and differences among participants between freestyle and *Polo* drill swimming. This supports the importance of providing both group- and individual-based analysis, especially at the high-performance level, in order to extract all available information from the data (Ball et al., 2003b). For example, the group-based analysis revealed that the medial-lateral range of the finger and wrist were not significantly modified when *Polo* drill swimming within the entry and catch phase of the stroke cycle. While the finger and wrist medial-lateral range was not significantly different for participants SW1, SW2, SW4 and SW6, participant SW5 showed significantly greater finger and wrist medial-lateral range values when performing the *Polo* drill. Further, unlike the group-based results, participant SW5 also displayed greater elbow extension at the catch instant while no significant differences were displayed in SV, finger velocity and the relative entry and catch duration. As participant SW5 was a middle-distance swimmer, the greater finger and wrist lateral range values throughout the underwater stroke phases may support the ‘S’-shape pull path typically displayed in middle- and long-distance swimmers swimming at maximum pace (Sanders et al., 2017; Takagi et al., 2016). However, for the remaining middle- and long-distance participants in this study, the finger and wrist did not display significantly greater lateral motion when performing the *Polo* drill. Sanders et al. (2019) suggested that variability in the lateral path of the hand exists due to the many degrees of freedom to be controlled. Therefore, the hand path adopted by participant SW5 is suggested to be a compromise between generating efficient propulsion and compensating changes in constraints such as breathing, swim pace variation and segment/joint contributions. Given the goal of the drill is to improve hand entry position, it is possible that participant SW5 did not explicitly focus on a consistent hand position in the entry and catch phase of the stroke when *Polo* drill swimming (Button, Macleod, Sanders, & Coleman, 2003; Coleman & Rankin, 2005; Sanders et al., 2019). Equally, the *Polo* drill may not be a suitable practice task to improve hand entry position for SW5 and may require the design of an alternative practice design or skill progressions to achieve this specific goal.

6.5.2.2 Pull and push phases

Even though the group-based analysis revealed that the overall medial-lateral range of the wrist and elbow was smaller within the pull phase when *Polo* drill swimming (see Chapter 5, Table 5.11, p. 148), this was not observed for all participants. In the pull phase, individual-based analysis revealed that participants SW1 and SW5 displayed a significantly larger finger medial-lateral range of motion when performing the *Polo* drill, returning large effect sizes. The larger medial-lateral range of motion of the hand could be considered a performance adaption to *Polo* drill swimming as both participants displayed no significant difference in SV between freestyle and *Polo* performance despite the greater finger velocity and SR (Guignard, Rouard, Chollet, Hart, et al., 2017). Additionally, these participants displayed a significantly smaller shoulder and hip vertical displacement range which support the suggestion from previous studies that hand motion is influenced by body roll (Guignard, Rouard, Chollet, Hart, et al., 2017; Psycharakis & Sanders, 2010; Sanders et al., 2017). While participant SW2 and SW4 also displayed significantly smaller shoulder and hip vertical displacements within the pull phase, both the finger and wrist medial-lateral ranges of motion displayed no significant differences. This contradicts previous suggestions and indicates that despite smaller shoulder and hip shoulder vertical displacement ranges when *Polo* drill swimming, hand motion may not necessarily be significantly influenced in the pull phase for all participants. The smaller hip vertical displacement ranges, however, may have influenced the significantly lower SV when *Polo* drill swimming (Andersen et al., 2018; McCabe et al., 2015; Psycharakis & McCabe, 2011; Psycharakis & Sanders, 2008).

In the push phase, both sprint-distance participants SW1 and SW4 showed a significantly greater finger medial-lateral range of motion when performing the *Polo* drill. Participant SW4 also displayed a less flexed elbow angle at the shoulder instant which is commonly seen in competition by sprint-distance swimmers (Sanders et al., 2017). From a coaching perspective, the *Polo* drill is prescribed to improve swimmers hand position and motion in both the entry and catch and pull phase of the stroke. Therefore, the larger finger medial-lateral range of motion in the pull and push phases may not be transferable to sprint-distance events as a small medial-lateral hand path is generally favoured (Guignard, Rouard, Chollet, Hart, et al., 2017; Sanders et al., 2017). However, for participant SW4, the *Polo* drill may help promote a similar hand entry and less flexed elbow angle at the shoulder instant representative of competition pace freestyle swimming. These individual differences indicate that future research is required to see specifically if and how drill performance alters technique relative to competition performance from an individual-based analysis perspective.

6.5.3 Group- and individual-based analysis comparison

The main findings revealed that five of the six participants presented significant, individual-specific differences in upper-limb kinematics between freestyle and *Long Dog* drill swimming within the propulsive phase of the stroke cycle. This is in contrast to the group-based analysis where the results suggested that the *Long Dog* drill had a trivial to no effect on freestyle upper-limb kinematics (see Chapter 5, section 5.4.1.3, p. 137). Participant SW2, however, displayed no significant differences in the upper-limb movement, shoulder and hip displacement and trunk inclination, similar to the group-based analysis. While the group-based analysis presented a significantly shorter average relative propulsive phase duration during the *Long Dog* trials, participant SW2 showed no significant differences. This suggested that although the *Long Dog* drill may represent slow-paced freestyle in training for participant SW2, there may not be any performance advantages doing this drill as opposed to swimming full freestyle in training. Consequently, this supports the inclusion of an individual-based analysis approach as additional information specific to the individual athlete that might be masked in a group-based analysis approach (Ball & Best, 2012; Ball et al., 2003a; Bates et al., 2004).

Inspection of the finger trajectories between freestyle and *Polo* drill swimming highlighted intra-individual variability as well as inter-individual difference in participant's stroke signatures. For example, participant SW3 displayed a larger lateral sweep within the propulsive phase of the freestyle stroke compared to participant SW4 (refer to Figure 6.4, p. 192). Participant SW3 was a long-distance swimmer and participant SW4 was a sprint-distance swimmer. However, contrary to the group-based analysis, participant SW3 displayed no significant differences in race parameters and stroke phase durations between freestyle and *Polo* drill swimming. Participant SW3 also displayed no significant differences in hand entry position. Subsequently, for participant SW3, there may not be any improvement to freestyle arm coordination when performing the *Polo* drill. This example shows how *Polo* drill swimming can influence temporal and kinematic parameters differently depending on the swimmer. Therefore, the *Polo* drill may not be suitable to improving hand entry position and arm coordination for all swimmers, as suggested from the group-based analysis, especially at the high-performance level. Additionally, as the participants assessed in this study varied in swimming distance specialisation, the *Long Dog* and *Polo* drill may influence stroke kinematics differently between individual swimmers (Guignard, Rouard, Chollet, Hart, et al., 2017; Sanders et al., 2017).

6.5 Conclusion

Biomechanical analysis of the freestyle stroke has shown that the position and motion of the hand has a direct influence on the generation of propulsion, inter-limb coordination and body alignment (Maglischo, 2003; Sanders et al., 2017). The *Long Dog* drill is prescribed to help swimmers improve or condition the body rotation, body alignment and the hand position within the pull phase of the freestyle stroke. Additionally, the *Polo* drill is prescribed to help swimmers improve or condition the hand position within the entry and catch and pull phases of the freestyle stroke (Brackley, Barris, et al., 2020; Lucero, 2015). This study aimed to investigate key freestyle movement and performance characteristics expected to be improved by the *Long Dog* and *Polo* drill from an individual-based analysis approach. The individual-specific differences ranged in the type and number of significant kinematic differences between freestyle and drill swimming. Further, the magnitude (i.e., trivial, small, moderate, large) and direction (i.e., greater or smaller) of these kinematic differences varied between freestyle and drill parameters per participant.

The individual-based analysis of the *Long Dog* drill revealed intra-individual similarities in the freestyle trunk inclination within both the pull and push phases of the stroke. This is in agreement with the findings from the group-based analysis in Chapter 5. However, all participants exhibited upper-limb kinematic differences between freestyle and *Long Dog* drill swimming. Notably, the middle-distance female participants displayed no significant differences in upper-limb displacements and trajectories when *Long Dog* drill swimming compared to the freestyle trials. Whereas one of the sprint-distance swimmers, SW4, showed a larger finger lateral range of motion and finger trajectories not representative of the hand pull path typically adopted in competition (Guignard, Rouard, Chollet, Hart, et al., 2017; Sanders et al., 2017). While the *Long Dog* drill showed no significant differences in trunk inclination values to freestyle, coaches may want to closely assess if the drill improves and represents the individual swimmer's body rotation and upper-limb kinematics for competition performance.

The significantly greater trunk inclination displayed when performing the *Polo* drill is supported by the findings presented in Chapter 5. However, similar to the *Long Dog* drill individual-based analysis, each participant displayed intra-individual variability as well as inter-individual difference in stroke signatures between freestyle and *Polo* drill performance. These findings highlighted the need for individual-based analysis to be used in conjunction with group-based analysis, especially at the high-performance level. Coaching recommendations may need to be tailored to the individual rather than developing a 'perfect' swimming technique model of 'good' technique.

6.6 Contribution of chapter to the aims of the thesis

The aim of Study Three (Chapter 6) was to extend the findings in Study Two (Chapter 5) and biomechanically compare the kinematics of full freestyle and drill swimming on an individual-basis. The findings contributed to answering the second aim of this thesis, identifying kinematic differences between freestyle and the two commonly prescribed upper-limb drills from an individual-based analysis perspective. The inclusion of both a group- and individual-based analysis provided a more comprehensive understanding of the immediate effect drill swimming has on freestyle performance.

Chapter 7: General Discussion and Conclusion

7.1 Introduction

In competitive swimming, the freestyle stroke is the fastest and most efficient form of human locomotion (Seifert, Boulesteix, et al., 2005; Seifert, Toussaint, et al., 2010; Skorski et al., 2014). The upper-limbs account for approximately 68% of total propulsion which has led to extensive research on the key characteristics underpinning the freestyle technique (Morouço, Marinho, Izquierdo, et al., 2015; Swaine et al., 2010). However, despite the importance of freestyle technique for efficient and fast swimming, the practice approaches prescribed to help develop or improve key technical characteristics are not well understood. Following a review of the literature in Chapter 2, it was identified that there is clear scope for research to both identify and biomechanically investigate the current practice approaches prescribed in swimming to improve freestyle technique. The general aim of this thesis was to assess the efficacy of current swimming practice drills for improving key movement and skill characteristics expected in competition performance. The specific aims of this thesis were to:

1. Identify the current practice approaches prescribed by elite swimming coaches for developing freestyle technique and align against the representative learning design (RLD) framework (Chapter 3).
2. Biomechanically compare movement kinematics between freestyle and commonly prescribed freestyle drills from a group- and individual-based analysis approach (Chapter 5 and 6).

This final chapter aimed to consolidate the key findings from each of the experimental studies in this thesis. Importantly, this thesis made one of the first attempts to apply the theoretical notions of RLD to the examination of common practice approaches in the sport of swimming. The methodological and practical implications of adopting RLD within this program of work are discussed with the aim to link together each of the studies presented.

Suggestions for future research are provided, in addition to the limitation of the methods used.

7.2 Main findings

7.2.1 Coaches' perspective towards skill acquisition in swimming (Chapter 3)

Study One (Chapter 3) provided important insights of the current practice approaches used by elite swimming coaches to develop fundamental skills for freestyle performance. This was important to contextualise the type of practice tasks currently being prescribed by elite swimming coaches to teach and condition key technical aspects in freestyle in Australia. Further, this was one of the first attempts in the swimming coaching literature to investigate the learning processes underpinning enhanced performance.

It was identified that freestyle drills that "break the stroke down" or decompose the stroke into smaller components are typically prescribed by swimming coaches. The findings confirmed previous suggestions that swimming practice tasks typically decompose the full skill into component parts (Seifert et al., 2013). The essence to skill acquisition, according to this traditional practice approach, is the ability to consistently and autonomously replicate a task movement that has been grooved to perfection in training (Davids et al., 1994; Seifert et al., 2013). However, contemporary theories on skill acquisition have criticised such practice approaches as they fail to consider the circular coupling between an individual and their performance environment, including the wide array of constraints which influence an individual's learning and performance (Davids et al., 2017; Newell, 1986; Seifert et al., 2013).

The prescription of drills was based on coaches' understanding of the key fundamentals required for efficient and fast freestyle. These key fundamentals included body alignment, arm coordination, leg kick, breath timing and stroke rhythm.

Consequently, to improve or reinforce these skills, the five drills that coaches prescribed the most included *Single-arm*, *Long Dog, Polo, Kicking* and *Sculling*. With the expressed purpose of developing one of the freestyle fundamentals listed above, the findings also showed that drills were generally performed in the warm-up in a mixture of drill and full freestyle swimming progressions. Based on theoretical understandings and practical applications of the RLD framework, it has been suggested drills that decompose the movement can significantly change key characteristics of the skill not representative of when performed as a whole in competition (Barris, Davids, et al., 2013; Pinder, Davids, et al., 2011b; Reid et al., 2010). This was unconfirmed in the swimming skill acquisition and biomechanics literature. Hence, key stroke characteristics expected to be improved when drill swimming required biomechanical assessment, using theoretical underpinnings from RLD (Pinder, Davids, et al., 2011b). The specific upper-limb drills assessed in Study Two and Three (Chapter 5 and 6) were selected based on the findings from this study.

7.2.2 Methodology of 3D kinematic assessment in swimming (Chapter 4)

Following the insights gathered from Study One (Chapter 3) in regards to the type and prescription of freestyle drills most commonly used by coaches, Chapter 4 provided a detailed description of the methodological procedures undertaken for the examination of the drill and freestyle technique. The current setup allowed for the assessment of drill and freestyle technique under realistic conditions. The swimmers recruited for data collection often trained at the pool used and regularly performed the drills under investigation. Using the findings from Study One (Chapter 3) as a guide, the experimental procedures were also representative of how coaches described prescribing drills in training. These factors increased the ecological validity of the findings in this thesis and differentiated the methodology from previous research in this area.

7.2.3 The effect of drill swimming on freestyle kinematics (Chapter 5 and 6)

Given the training insights from Study One (Chapter 3) and the 3D swimming kinematic analysis viability detailed in Chapter 4, Study Two and Three (Chapters 5 and 6) examined two of the most commonly prescribed upper-limb drills, *Long Dog* and *Polo*. The current investigations were unique as they were the first to specifically assess the key movement and performance characteristics expected to be improved by freestyle drill swimming from a group- and individual-based analysis approach.

7.2.3.1 Group-based analysis (Chapter 5)

The results showed no significant differences in shoulder movement, trunk inclination and upper-limb motion in the pull phase of the stroke between freestyle and *Long Dog* drill swimming. As the task goal of the drill was to improve or reinforce body rotation, trunk alignment and the hand path within the pull phase of the freestyle stroke (see Chapter 3, Table 3.1, p. 70), the results suggested that the drill represented the specific freestyle task goals. However, to achieve the correct alignment and hand pull path, the swimmers compensated by using a significantly larger vertical range of motion of the shoulder within the push phase. It can therefore be inferred that the removal of the above-water recovery phase when performing the *Long Dog* drill can result in a greater shoulder roll magnitude within the push phase of the stroke.

The *Polo* drill results showed that despite the significant differences in upper-limb and temporal kinematics between freestyle and *Polo* drill swimming, the movement adjustments of certain variables could have some positive transfer between *Polo* drill swimming and maximal race-pace freestyle. For example, a straighter motion of the upper-limbs when *Polo* drill swimming may represent the pull path typically displayed by sprint-distance swimming in competition (Sanders et al., 2017). Further, it was concluded that *Polo* drill swimming may act as a task constraint manipulation that leads to higher stroke rate (SR) values and inter-arm coordination adaptations transferable to movement adjustments beneficial to maximal race-pace freestyle (Guignard, Rouard, Chollet, Hart, et al., 2017). This confirms the current task goals of the *Polo* drill. However, similar to the prescription of the *Long Dog* drill, coaches need to be mindful of the negative affect the *Polo* drill has on other aspects of the freestyle stroke. Namely, having the head above-water when performing the *Polo* drill displayed a significantly greater trunk inclination, disrupting the streamlined body position.

The findings reinforced what swimming coaches understand in regard to the negative consequences associated with drill prescription, as described by one of the interviewed coaches in Study One (Chapter 3):

> I would say, and this is the problem with any drills that if you're using it to focus on a specific aspect, nine times out of ten it's going to negatively affect at least one other part of the stroke. So, whenever you use a drill you've got to understand is… so you've got to be very mindful of the affect. (SC4)

Further, the significantly slower swimming velocity (SV) when performing both the *Long Dog* and *Polo* drill did not reflect the coaches' perspective in regards to performing drills at race specific speeds (see Chapter 3, section 3.4.1.3, p. 72). Consequently, coaches may want to closely assess if the drills improve and represent the swimmer's body rotation, trunk inclination and upper-limb kinematics for competition performance. In addition, the speed in which drills are performed may differ depending on the skill level of the athlete and if the drill is prescribed to either improve or reinforce a particular skill.

7.2.3.2 Individual-based analysis (Chapter 6)

Building from the findings in Study Two (Chapter 5), Study Three (Chapter 6) aimed to compare the kinematics of full freestyle swimming and the two commonly prescribed upper-limb drills, *Long Dog* and *Polo*, from an individual-based analysis approach. The findings demonstrated how both drills can influence temporal and kinematic parameters differently depending on the swimmer. The group-based analyses in Study Two (Chapter 5) provided important information relating to the biomechanical effect drills can have on performing the full freestyle stroke. However, the individual-based analysis provided additional information specific to the individual athlete that was masked in the group-based analysis approach (Ball & Best, 2012; Ball et al., 2003a; Bates et al., 2004).

7.3 Methodological implications

This thesis made several important methodological contributions and in turn identified key considerations for future research. Of particular note, was the adoption of a mixed methods approach where both qualitative and quantitative methods were used. Additionally, the sampling of elite participants and the inclusion of both group- and individual-based analysis was used in the assessment of drills compared to freestyle performance.

7.3.1 Mixed methods

The use of mixed methods has grown in popularity in sport science research where recent studies have highlighted the power of combining qualitative and quantitative approaches (Maloney et al., 2018; R'Kiouak, Saury, Durand, & Bourbousson, 2016). These approaches offer more complete insights to corroborate findings (Hesse-Biber & Johnson, 2013). This thesis provided an example of how qualitative methods used in Study One

(Chapter 3) helped inform the experimental design protocols in Study Two and Three (Chapters 4, 5 and 6).

The qualitative methods adopted in Study One (Chapter 3) involved semi-structured interviews with 20 elite swimming coaches in Australia. The intention of this approach was to collect data on the underlying skill acquisition approaches adopted to inform specific training tasks. This study revealed which drills were commonly prescribed to improve or reinforce freestyle technique and how these drills are typically applied in training. Coaches mentioned that drills are routinely performed in the warm-up at distances of 200 - 800 m broken into 25 - 50 m drill followed by 25 - 50 m of freestyle (see Section 3.4.1.3, p. 72). The insights from this study allowed the action fidelity of the two commonly prescribed upper-limb drills to be tested under representative experimental protocols to those prescribed by coaches (Chapter 5 and 6).

Additionally, expert coaches have years of sport specific knowledge which can be useful in understanding the relevant constraints and complexities relating to performance (Greenwood et al., 2012, 2014). Integrating the experiential knowledge of expert coaches with empirical data has proven to provide valuable foundational support for practical applications in learning design (Davids et al., 2017; Greenwood et al., 2014). While informative, a challenge with coach interviews is understanding the coaches' terminologies and language. To combat this, probes were used throughout the interviews in Study One (Chapter 3) to engage further elaboration or to ensure the participant's description was accurately understood (Louise & While, 1994; Patton, 2002). This approach ensured that the responses given were consistent in terms of depth and complexity yet allowed the flexibility to pursue responses beyond the scope of the specific interview questions (A. Fontana & Frey, 2005; Hardy et al., 2017). Further, the interview was approached from the perspective of a student in swimming attempting to understand how a successful swimming coach approached training. This allowed the demonstration of "empathic neutrality" (A. Fontana & Frey, 2005; Patton, 1999, 2002). The qualitative insights from the coach interviews in Study One (Chapter 3) provided context in regard to why and what freestyle drills are typically being prescribed. This information also informed the design of a testing protocol representative of how freestyle drills were performed in training.

7.3.2 Participant selection

The participants sampled in this thesis were limited to elite freestyle swimmers to increase the likelihood participants had well established freestyle stroke characteristics (McCabe & Sanders, 2012; Nikodelis et al., 2005; Pyne et al., 2004). To be eligible, participants had to: (a) attend national and international level competitions on a regular basis, (b) have a minimum of two years specialised in their chosen distance as a freestyle swimmer and (c) have no injuries nor be in the process of recovery at the time of testing.

Previous studies have demonstrated how elite swimmers in competition are able to achieve higher and more stable spatial-temporal parameters while minimising SR compared to sub-elite swimmers (Kolmogorov, Rumyantseva, Gordon, & Cappaert, 1997; Seifert, Chollet, et al., 2005). Elite freestyle swimmers are also able to adopt a more streamlined body position, while maintaining a lower active drag, by using propulsive forces in a more efficient way (Kolmogorov et al., 1997). The hips and shoulders of elite swimmers appeared to rotate more symmetrically and with greater amplitude compared to lesser experienced swimmers (Cappaert et al., 1995). In addition, elite swimmers appear to be able to better maintain arm coordination patterns when turning their head to take a breath compared to sub-elite swimmers (Seifert, Chollet, et al., 2005).

It has been argued that elite athlete populations may benefit most from training practices that are representative of the specific context intended to be simulated (Dicks et al., 2008). Consequently, when examining the technical differences between freestyle and drill performance, recruiting swimmers with a higher skill level can allow the findings to be interpreted and applied to elite swimming training programs. The current literature available on the effect of drill swimming on freestyle performance were limited to national and regional level swimmers (Arellano et al., 2010; López et al., 2002). Therefore, this thesis extended existing literature by recruiting an elite population and investigating the specific movement and performance characteristics prioritised in commonly prescribed upper-limb drills. Despite the high skill level of the participants within this thesis, the small sample size presented challenges in the statistical methods used that affected the generalisability of results (Sands, McNeal, & Stone, 2005). In order to help alleviate these challenges, an individual-based analysis approach was also included in this thesis.

7.3.3 Group and individual-based analysis

When examining technical aspects of a skilled movement, the combination of both a group- and individual-based analysis approach has been recommended to ensure all important information is extracted (Ball & Best, 2012; Ball et al., 2003a, 2003b). This thesis used two analysis approaches: (i) group-based analysis which involved the evaluation of a problem across a group of subjects and (ii) individual-based analysis which involved the evaluation of a problem within a single-subject (Bates et al., 2004). A group-based analysis approach was firstly used to identify the key kinematic and performance differences between freestyle and drill swimming (Chapter 5). This was followed by an individual-based analysis approach in order to provide individual-specific findings relating to the effect of drill swimming on freestyle performance (Chapter 6).

Using an elite population sample, the group-based analysis findings from Study Two (Chapter 5) provided useful information in understanding the action fidelity of freestyle drills that was not specifically evident in the individual-based analysis reported in Study Three (Chapter 6). For example, the group-based results suggested that the *Polo* drill may support greater propulsive continuity of the two arms transferable to inter-arm coordination adaptations required in competition. Conversely, the individual-based analysis results did not specifically indicate inter-arm coordination adaptations transferable to maximal race-pace swimming for all swimmers. In turn, the potential positive modifications to inter-arm coordination when *Polo* drill swimming may not have been detected using only an individual-based analysis approach. The findings from Study Two (Chapter 5) were useful in developing a general understanding of the effect drill swimming has on freestyle kinematics and performance. An additional advantage of group-based analysis is that it allows for the results to be generalised to a larger population (Bates et al., 2004). While this information can be used to objectively guide drill prescription in improving specific technical aspects of the freestyle stroke across distance specialisations, it is important to consider that the presented results may not be applicable to all elite individuals.

Studies have revealed that individuals adopt varying movement responses to achieve a particular performance outcome, resulting in an increase in inter-subject variability (Bates et al., 2004; Button et al., 2006; Caster & Bates, 1995). Consequently, the statistical power of the group-based analysis would reduce which can result in a false support of a null hypothesis depending on the distribution of subjects (Bates et al., 2004; Button et al., 2006; Caster & Bates, 1995). Given movement variability within expert individuals can also be considered functional when it supports the performance outcome required (Bartlett et al., 2007; Davids & Glazier, 2010; Davids et al., 2003), individual-based analysis can provide important information relating to a skill that might be masked or considered as ‘noise’ within a group-based analysis approach (Ball & Best, 2012; Ball et al., 2003a; Bates et al., 2004; Dufek et al., 1995).

Using an individual-based analysis approach in Study Three (Chapter 6) provided additional information that was not specifically evident in the group-based analysis (Chapter 5). For instance, when performing the *Long Dog* drill, both participant SW3 and SW6 (long-distance swimmers) displayed a significantly deeper maximal vertical displacement of the finger compared to freestyle, whilst there were no significant differences observed on a group basis. This may have been associated with the significantly greater elbow flexion at the catch instant. Studies have shown, however, that the elbow is less extended at the catch instant for long-distance freestyle swimmers where an ‘S’-shaped pull path is typically adopted (Nakashima et al., 2012; Payton et al., 1999). That being so, the removal of the above-water recovery phase when *Long Dog* drill swimming presents upper-limb modifications that may not be representative to the pull depth and elbow flexion typically observed in long-distance freestyle swimmers. This demonstrated that the findings from the group-based analysis may have provided misleading information for certain participants (Ball & Best, 2012; Ball et al., 2003a, 2003b; Bates et al., 2004). The group-based analysis suggested that the *Long Dog* drill may represent freestyle upper-limb kinematics, although failed to account for individuals’ freestyle distance specialisation.

The individual-based analysis also revealed contrasting findings between individuals. Participant SW5 showed significantly greater finger and wrist medial-lateral range values in the entry and catch phase when performing the *Polo* drill, while four of the remaining participants showed no significant differences. The hand path adopted by participant SW5 is suggested to be a compromise between generating efficient propulsion and compensating changes in constraints such as breathing, swim pace variation and segment/joint contributions. Given the goal of the drill was to improve or reinforce hand entry position, it is possible that participant SW5 did not explicitly focus on a consistent hand position in the entry and catch phase of the stroke when *Polo* drill swimming (Button et al., 2003; Coleman & Rankin, 2005; Sanders et al., 2019). Also, the *Polo* drill may not be a suitable practice task to improve hand entry position for SW5 and may require the design of an alternative practice design or skill progressions to achieve this specific goal. This demonstrates that practice tasks are to be designed based on the specific needs of the athlete (Pinder & Renshaw, 2019).

Incorporating both group- and individual-based analysis increased the complexity of the research design in this thesis. The combination of both group- and individual-based analysis provided a more thorough understanding of the immediate effect drills can have on freestyle performance. Further, the individual-based analysis provided important information relating to each individual’s unique stroke signature and variability within trials. This indicated that coaches and practitioners need to evaluate swimmer’s technique on an individual basis. The findings from Study Two and Three (Chapter 5 and 6) support the recommendation made by previous researchers that the inclusion of both a group- and individual-analysis approach is appropriate in biomechanical research in order to extract all important information related to a particular skill or movement (Ball & Best, 2012; Ball et al., 2003a).

7.4 Practical implications

7.4.1 Coaches' perspective towards skill acquisition in swimming

Coaches' insights towards drill prescription from Study One (Chapter 3) informed the testing methodology of Study Two and Three (Chapter 5 and 6), where the most commonly prescribed freestyle drills were assessed in a training setting. This ensured that the testing outcomes accurately reflected how drills were currently prescribed and allowed for practical insights to be communicated directly back into elite swimming programs.

Understanding coaches' philosophies can help researchers and sport practitioners expand their sport-specific knowledge and speak the coaches' language when discussing current literature (Dehghansai et al., 2019; S. J. Williams & Kendall, 2007). This is important as the gap between 'science' and 'practice' can be exacerbated when scientists utilise terminologies that fail to align with the language spoken in sport (Dehghansai et al., 2019; Farrow et al., 2013). Findings from Study One (Chapter 3) were able to provide an understanding of coaches' perspective towards skill acquisition. The interview process also created opportunities for the coach to expand their understanding of contemporary skill acquisition theories. Such conversations between a coach and sport practitioner can create opportunities for coaches to comfortably collaborate with skill acquisition consultants to create individualised learning designs (Dehghansai et al., 2019; Pinder & Renshaw, 2019; Stone, Rothwell, Shuttleworth, & Davids, 2020).

7.4.2 The effect of drill swimming on freestyle kinematics: Group-based analysis

Applying the concepts of RLD to training can ensure practice tasks simulate key aspects of competitive performance (Barris, Davids, et al., 2013; Dhami et al., 2004; Pinder, Davids, et al., 2011b). Training tasks that are more representative of the performance setting have been suggested to produce learning outcomes that can be applied in competition, therein enhancing performance (Vilar et al., 2012). For this reason, the aim of Study Two (Chapter 5) was to understand if there were differences between drill and full freestyle swimming.

In Study Two (Chapter 5), the effect of *Long Dog* and *Polo* drill swimming on freestyle kinematics were assessed from a group-based analysis approach. While the results revealed that the specific *Long Dog* drill parameters represented those of full freestyle, the movements that emerged may not be functional in the competitive environment (Araújo et al., 2007). Coaches considering using the *Long Dog* drill to improve the hand path within the pull phase are recommended to explore the integration of key skill acquisition principles, such as the constraints-led approach or RLD, in the training design (Pinder & Renshaw, 2019). Further, it is important that the intentions of drills are explicitly communicated and discussed with the athlete rather than prescribing such drills in the warm-up with no specific goal discussed. This was noted by one of the interviewed coaches in Study One (Chapter 3) as a challenge with current drill prescription in swimming:

> You tell me a program you've been to and they [the athletes] haven't just flopped up and down in the warm up and the coach hasn't been on the side watching what they're doing… So, if a coach comes in and writes a session on the board and then carries on writing once the swimmers have got in [the water], he isn't going to be looking at the skill acquisition. So, to say they do the drills and all that in the warm up, it doesn't mean a lot. (SC3)

The task goal of the *Polo* drill was to help swimmers improve or reinforce their hand position and arm coordination within the entry and catch and pull phases of the freestyle stroke (see Chapter 3, Table 3.1, p. 70). The results confirmed that the *Polo* drill could facilitate a stable hand position at entry. While SV was slower and trunk inclination was greater, the findings also suggested that the *Polo* drill could be considered a task constraint manipulation that leads to higher SR values and inter-arm coordination adaptations transferable to maximal race-pace freestyle. Coaches may benefit from prescribing the *Polo* drill within a skill progression as also noted by one of the interviewed coaches in Study One (Chapter 3).

> A series of drills might need to be linked, like I've just talked about, to get to the outcome in the swimming that you're after. Often, we just don't use a drill in isolation. There's usually a progression then to swim. Then we could continue to swim to consolidate. There's no value in doing some drills, say, in freestyle, and not swimming in the end. (SC11)

Additionally, it is important to assess whether the technical skills focused on during a particular drill or intervention transfers and aligns to the requirements of freestyle performance in competition. This study provided empirical data to confirm or question current freestyle 'technique' drills. The results provided a biomechanical comparison between drill and full freestyle swimming. This information is useful as it encourages coaches and sport practitioners to carefully assess whether the particular drill prescribed fulfils the desired performance outcome and supports the skills required in competition.

7.4.3 The effect of drill swimming on freestyle kinematics: Individual-based analysis

In order to design or prescribe a practice task that achieves a highly specific goal, Pinder and Renshaw (2019) emphasised the importance of having a deep understanding of the performance demands in competition and the individual athlete. Examination of the effect of drills on freestyle performance on an individual-basis in Study Three (Chapter 6) highlighted how swimmers had unique stroke signatures. These finding have important implications for the skill development of swimmers as differences in physical characteristics and race distance specialisation may require different practice tasks.

This thesis provided information encouraging coaches and sport practitioners to biomechanically evaluate swimmers' technique on an individual-level. While the interviewed coaches in Study One (Chapter 3) mentioned the support of individualised training programs, anecdotal training observations have suggested that coaches typically prescribe drills to the entire squad rather than considering an individualised approach. Inspection of the individual stroke signatures presented in Study Three (Chapter 6) illustrated inter-individual difference in participant's stroke signatures. Therefore, providing one 'perfect' or 'model' freestyle technique may not be appropriate for all swimmers, especially at the elite level. As such, training tasks are to be tailored to an individual when targeting improvement in specific movement and performance characteristics.

A constraints-led approach, underpinned by RLD, offers a framework to support the design of individual tasks (Pinder & Renshaw, 2019; Seifert et al., 2013). Specifically, the manipulation of constraints may benefit the improvement of specific aspects of the freestyle stroke rather than the prescription of drills that decompose the skill into smaller components. For example, instead of prescribing the *Long Dog* drill to help a swimmer improve freestyle trunk alignment, holding a pull-buoy between the thighs may help the swimmer maintain a horizontal and streamlined body position (Gourgoulis et al., 2014; Zamparo et al., 2009).

Additionally, the findings from Study Two (Chapter 5) suggested that the greater trunk inclination when *Polo* drill swimming could lead to a lower leg kick frequency, resulting in a leg-sinking effect (Gourgoulis et al., 2014; McCabe et al., 2011; Sanders & Psycharakis, 2009). Having the swimmer hold a pull-buoy between the thighs when *Polo* drill swimming may help reduce the leg-sinking effect (Gourgoulis et al., 2014). Seifert et al. (2013) also suggested that the use of hand paddles or fins increases the propulsive surfaces in order to help the swimmer improve the hand position and pull trajectory. This simplifies the task without using drills like the *Long Dog* or *Polo* drill that decomposes it which is considered to be more beneficial to skill learning (Barris, Davids, et al., 2013; Dicks et al., 2008; Renshaw et al., 2010; Renshaw et al., 2009).

Depending on the desired performance outcome, drills that decompose the skill into smaller components may be an appropriate practice task for a specific individual (Pinder & Renshaw, 2019). The findings from Study Three (Chapter 6) revealed that drills may represent specific freestyle parameters in training for some individuals. However, Guignard, Rouard, Chollet, Hart, et al. (2017) suggested that the upper-limbs may follow a different trajectory at increased SV, from slow to maximal pace freestyle. Therefore, coaches and sport practitioners are encouraged to carefully test the skill under ‘pressure’, simulated performance contexts or varying progression to assess learning and ensure performance outcomes correspond to the specific goals of the drill.

7.5 Limitations of this thesis

Even though this was a novel approach to skill acquisition research is swimming, there are still some limitations to be acknowledged. Study One (Chapter 3) provided detailed insights into high-performance swimming coaches application of skill acquisition approaches in their design and prescription of training tasks. The study involved interviewing elite swim coaches in Australia. Therefore, it is possible that their international counterparts may differ in practice design and prescription as coaching pathways and accreditations vary internationally. As eight of the participants had not only coached successfully in Australia but internationally in America, New Zealand, South Africa, Dubai, Great Britain and the Netherlands these differences may be minimal.

The relationship between members of the research team should also be acknowledged as a potential limitation and influencer of the results. Some members of the research team had or currently work as a biomechanist or skill acquisition specialist with some of the participants. This may have shaped some of the participants current practice approaches and hence their responses provided. An additional point worth noting is that the present sample consisted of only one female coach. This imbalance is an illustration of the male-dominance in elite swimming coaching where out of the 24 ‘Platinum’ accredited coaches in Australia, only three are female. Further research is required to establish whether practice prescriptions from female swimming coaches, regardless of their accreditation, are congruent with current findings.

Participants were requested to provide answers directly associated with their current training programs. While the open question style of interview promoted honest answering, it is possible that the responses given may differ somewhat from their actual practice prescriptions. Including training observational notes with the interview data may have added further clarity and trustworthiness to the data (Polkinghorne, 2005).

Study Two and Three (Chapter 5 and 6) provided detailed and relevant findings regarding the immediate effect of drills on full freestyle swimming. While these studies were novel in providing specific temporal and kinematic findings relating to the goal of the drills, some limitations must be recognised. Firstly, the aquatic swimming environment presented a number of challenges in regards the data capture and analysis. While recent technological advances have aided the development of water-proof, wearable microsensors such as accelerometers, gyroscopes and magnetometers in swimming, this technology was not available or adequately validated at the time of data collection. In turn, a 3D video-based system setup was utilised in this thesis as this method of biomechanical analysis has been used on multiple occasions prior to this thesis (de

Magalhaes et al., 2014; Elipot et al., 2009). The SwimPro camera system (SwimPro®, Newcastle, Australia) used in this thesis limited the motion of the swimmers recorded as they only sampled a frequency of 30 Hz. Sanders, Gonjo, et al. (2015) compared camera sampling frequencies at 25 Hz and 50 Hz and found that sampling at 25 Hz could yield reliable data for analysis. Given this, sampling at 30 Hz was considered acceptable for the analysis of the freestyle and drill kinematics.

Due to the length constraints of the calibration frame, only one complete stroke cycle could be captured and analysed per lap. Moreover, the four-lane indoor pool used in this study was not specifically designed for research and only allowed one side of the swimmer to be captured at a time. While swimming away from the start block, the right-side of the swimmer was captured whereas swimming towards the start block, the left-side of the swimmer was captured. Both the right and left side of the swimmer were combined for analysis. As movement asymmetries exist and swimmers tend to have a dominant arm (Morouço, Marinho, Fernandes, & Marques, 2015; Sanders, Thow, & Fairweather, 2011), combining both the right and left side of the swimmer for analysis may explain the large standard deviations displayed within some of the temporal and kinematic variables measured. Additionally, the vertical range of the shoulder and hip were measured as an alternative indicator of body rotation as the current experimental setup and pool did not enable body roll to be measured. To draw more accurate conclusions on the effect drill swimming has on body rotation, an experimental design that allows this parameter be measured should be considered in a future study.

Second, this study was limited to six participants. Due to this limited participant sample, the swimmers varied in distance specialisation and male and female data was combined in the group-based analysis. While the participants were specialised in a particular freestyle distance, it was common for swimmers to also compete across varying distances (McGibbon, Pyne, Shephard, Osborne, & Thompson, 2020). Further, in training, swimmers typically swim at different intensities and pacing strategies to develop physiological aspects regarded as deficient (Maglischo, 2003). Studies have reported differences in arm coordination adaptations and stroke length (SL) at race-pace freestyle between male and female freestyle swimmers (Seifert, Boulesteix, & Chollet, 2004; Seifert, Chollet, & Chatard, 2007). While anthropometric characterises may be partially responsible for the differences in performance parameters between male and female swimmers, the movement pattern of the swimmer’s limbs has been suggested to be a greater influencer of performance (Gourgoulis et al., 2014).

In regards to swimmers’ distance specialisation, McCabe et al. (2011) and McCabe and Sanders (2012) reported that sprint- and long-distance freestyle swimmers have similar upper-limb kinematics when swimming at race-pace. They also acknowledged that swimmers utilise a trajectory of the upper limbs under the water that suits the requirements of the swimming event (McCabe et al., 2011; McCabe & Sanders, 2012). Sprint-distance swimmers tend to adopt an ‘I’- shaped pull path whereas middle- and long-distance swimmers typically display the ‘S’-shape pull path (Guignard, Rouard, Chollet, Hart, et al., 2017; Sanders et al., 2017). This was observed in the stroke signature data in Chapter 6 where the long-distance participants displayed greater finger lateral range of motion compared to the sprint-distance participants. Despite this, the current sample included elite swimmers with national and international competition experience in Australia. Combining all participants was deemed appropriate as regardless of the distance specialisation, elite swimmers may have developed a unique stroking pattern (McCabe & Sanders, 2012). Further, anecdotal training observations have revealed that coaches prescribe the *Long Dog* and *Polo* drills to all swimmers regardless of their distance specialisation or gender. To minimise the impact of the small sample, multiple trials were analysed per participant and individual-based analyses was undertaken (Chapter 6). The individual-based analysis also provided unique insight on how drills can affect freestyle stroke kinematics differently per individual swimmer. Although a sample of under ten participants is common in swimming-related studies (de Jesus et al., 2016; Gourgoulis et al., 2014; McCabe & Sanders, 2012), a larger sample of similarly skilled swimmers is needed before more general conclusions can be drawn.

Thirdly, only the upper-limb and hip kinematics were analysed, restricting analysis to the lower limbs. This was based on the specific goals of the *Long Dog* and *Polo* drill. As such, it is acknowledged that this exploration of the effect of drill swimming on freestyle is limited to upper-limb and hip kinematics. The inclusion of lower-limb analysis may strengthen and extend the findings of these initial studies. Finally, while it is acknowledged that the movement adjustments of certain upper-limb variables when drill swimming may positively transfer to maximal race-pace freestyle, the studies could not confirm this possibility. Future research, designing a skill intervention, is required to investigate if and how drills alter freestyle technique in competition performance.

7.6 Future directions

The findings from this thesis proposed a number of interesting considerations to extend the work further. Firstly, while the 3D methodology employed to assess the drill and freestyle kinematics was highlighted as a strength of this thesis, researchers continue to explore new and innovative ways to assess 3D kinematics in swimming. The development of water-proof, wearable microsensors has opened new possibilities to biomechanically assess swimming and monitor performance in training (Guignard, Rouard, Chollet, & Seifert, 2017). Guignard et al. (2019) was able to investigate how upper to lower limb coordination dynamics varied at increasing swimming speed in a flume and pool using four inertial measurement units (IMUs). Data collection of this nature would not be restricted by the size of the pool and could be recorded continuously over an extended period of time. This would allow for more strokes to be analysed, which could uncover additional insights into how drills affect freestyle performance.

The use of a multi-digital camera setup for 3D quantitative analysis has become the gold standard in swimming (Sanders, Chiu, et al., 2015). However, the manual digitisation of anatomical landmarks and data processing procedures are labour intensive, reducing its effectiveness as a feedback tool in training (Le Sage et al., 2011; Mooney, Corley, Godfrey, Quinlan, et al., 2015; Phillips, Farrow, Ball, & Helmer, 2013). While IMUs continue to undergo rapid technological developments, recent studies in swimming biomechanics have demonstrated how some of the limitations encountered from 3D motion analysis may be alleviated using IMUs (Guignard, Rouard, Chollet, & Seifert, 2017). Given the limitations with the 3D methodology outlined in Chapter 4, the addition of IMUs could allow arm coordination and body rotation to be specifically assessed.

This thesis detailed how the action fidelity of two commonly prescribed upper-limb drills were biomechanically assessed. Ideally, the RLD framework includes the consideration of both functionality and action fidelity in the design of practice tasks (Pinder, Davids, et al., 2011b; Pinder et al., 2013). The 'representative practice assessment tool' (RPAT) was developed and validated as an applied assessment tool in tennis to assess the representativeness (i.e., functionality and action fidelity) of practice tasks (see Krause et al. (2018) for full details). Therefore, the biomechanical assessment of drills could include a modified RPAT, suitable for the sport of swimming, to evaluate how changes to task representativeness affect learning and skill transfer. This can also simply the use of RLD in the applied setting by enabling coaches to assess practice outcomes and the likelihood for skill transfer (Krause, Farrow, Pinder, et al., 2019; Krause et al., 2018).

Using sound theoretical frameworks and learning designs, the findings from Study Two and Three (Chapters 5 and 6) could be extended to include the design of a skill intervention. Pinder and Renshaw (2019) provided a case study on how a method of task simplification in long jump was used to improve technique. Practicing a simplified version of the whole task has been suggested to be more beneficial to skill learning as the perception-action link is maintained throughout practice (Barris, Davids, et al., 2013; Dicks et al., 2008; Renshaw et al., 2010; Renshaw et al., 2009). Hence, the design of skill interventions in swimming may benefit from employing methods of task simplification rather than task decomposition when working on specific technical changes in an individual (Seifert et al., 2013).

Coaches may benefit working with a skill acquisition consultant to ensure that the manipulation of constraints carefully considers the interaction of individual constraints and expected or predicted responses from the practice task (Pinder & Renshaw, 2019). Appropriate manipulations of constraints may prepare the swimmer to functionally respond to the competitive context of performance through adaptive behaviour (Seifert et al., 2013). Sport practitioners and coaches seeking to develop swimming technique in all of the form strokes could utilise methods such a manipulation of task constraints, underpinned by RLD principles, in order to challenge learners to search for their own movement solutions to a specific task (Dehghansai, Lemez, Wattie, Pinder, & Baker, 2020; Seifert et al., 2014). The results from Study Two and Three (Chapters 5 and 6) suggested that drills can influence freestyle stroke kinematics differently depending on the swimmer’s distance specialisation. An important next step for future research is to compare current drill prescription to maximal race-pace freestyle to see if drills are improving freestyle technique in competition performance. In addition, future research is to design an intervention comparing task decomposition drills with a RLD approach. It would also be interesting to examine the efficacy of specific practice tasks across a range of distance specialisations and skill levels (e.g., club-level, national or international).

7.7 Overall conclusion

The aim of this thesis was to examine the efficacy of current freestyle swimming practice approaches for improving key movement and skill characteristics expected in competition performance. The biomechanical literature is replete with empirical findings on the kinematic and kinetic features critical to efficient and fast freestyle (Guignard et al., 2019; Sanders et al., 2017; Toussaint & Beek, 1992). However, the examination of specific practice approaches prescribed to acquire and improve these biomechanical qualities is underrepresented in the current literature.

This thesis harnessed coaches' experiential knowledge and perspectives towards skill acquisition in elite swimming (Chapter 3). It was identified that coaches typically prescribed drills that decompose the skill of freestyle swimming into smaller components. The two most commonly prescribed upper-limb drills were *Long Dog* and *Polo*. Previous research has suggested that drills that decompose the movement skill can significantly change key characteristics of the skill not representative of when performed as a whole in competition (Barris, Davids, et al., 2013; Krause, Farrow, Buszard, et al., 2019; Pinder, Davids, et al., 2011b; Reid et al., 2010). While increasing the representativeness of practice tasks does not simply imply enhanced skill learning, it can impact whether the performance outcomes are desirable for the skills required in competition (Krause, Farrow, Pinder, et al., 2019).

In an attempt to understand the immediate effect drill prescription has on freestyle performance, Study Two and Three (Chapter 5 and 6) biomechanically assessed the two most commonly prescribed upper-limb freestyle drills using a 3D kinematic analysis approach (Chapter 4). The finding from Study Two (Chapter 5) suggested that although the *Polo* drill presented temporal and kinematic differences compared to freestyle, the higher stroke rate values and inter-arm coordination could be beneficial to race-pace freestyle. The *Long Dog* drill returned no significant differences in upper-limb characteristics compared to freestyle, yet may not represent the medial-lateral hand pull path at race-pace freestyle. The individual-based analysis results (Chapter 6) displayed how all swimmers displayed unique stroke signatures within and between freestyle and drill trials. Consequently, drill swimming can influence freestyle technique differently depending on the swimmer and distance specialisation. These findings highlighted the benefit of assessing whether performance outcomes correspond to the specific goals of the drill. At the elite level, a combination of both group- and individual-based analysis is needed in the examination of drill and freestyle performance.

The series of studies presented in this thesis demonstrated how the action fidelity of the two commonly prescribed upper-limb drills were assessed under representative experimental protocols to those prescribed by coaches. Practically, the assessment of the two freestyle drills, relative to freestyle performance, provided important insights into ensuring practice design aligns with the specific task goals of the individual and freestyle requirements. Specifically, for some swimmers, a particular drill may not represent the intended movement responses. Coaches and sport practitioners are encouraged to carefully test whether practice tasks or drills are functional for the swimmer’s freestyle performance priorities.

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Appendices

Appendix A: Participant information and consent forms (Chapter3)

INFORMATION TO PARTICIPANTS INVOLVED IN RESEARCH

You are invited to participate!

You are invited to participate in a research project entitled '**Exploring the transfer from drills to skills in elite freestyle swimming'.**

This project is being conducted by a student researcher, Victoria Brackley, as part of a PhD study at Victoria University (VU) in partnership with Swimming Australia (SAL). The PhD study is under the supervision of Prof. Damian Farrow and Dr. Kevin Ball from the Institute of Sport, Exercise and Active Living (ISEAL) at VU, Dr. Sian Barris from the South Australian Sports Institute (SASI) and Dr. Elaine Tor from the Victorian Institute of Sport (VIS).

Project explanation

The purpose of practicing skills in sport is to increase performance capability in competitive environments. Traditionally, drills are placed within the training environment to replicate adaptive movements and practice skills. However, it has been argued that many of these practice drills lack the capability to represent the behavioural and movement patterns required in the competitive environment.
Thus, the overarching aim of this project is to examine the efficacy of freestyle swimming training drills in relation to the full freestyle swimming stroke. More specifically, this PhD project aims to:

1. Establish the most commonly practiced freestyle drills used by elite Australia coaches;
2. Compare kinematic differences between each practiced freestyle drills and the full freestyle stroke in both the training and competitive environment; and,
3. Improve the design and implementation of swimming drills and training specific to the freestyle stroke.

The overall project hopes to address the gap in the literature and the practical uncertainties on how representative the drills performed by elite freestyle swimmers are to the full freestyle stroke seen in competition. Your contribution will help address the first aim of this project.

What will I be asked to do?

You are requested to participate in a once-off, private interview with the student researcher, Victoria Brackley. In the interview you will be asked either open or closed questions around the areas of general skill development, the use of specific drills and what influences your session design. The interview is anticipated to go for approximately 60 minutes in duration and will be digitally recorded.

What will I gain from participating?

Participating in this study will assist us in gaining an insight on how elite coaches, like yourself, address skill development and use freestyle drills within the training setting. This will help shape which drills will be assessed in the subsequent studies within the entire PhD project. Additionally, your contribution and input into this project will help put Australian swimming at the forefront in regards to developing even more effective training protocols which is planned to lead to even more success.

How will the information I give be used?

The digitally recorded interviews will be transcribed verbatim. Before the transcriptions will be analysed and coded, you, as the participant, will receive a copy of the interview transcription for verification of accuracy. The completed online survey results, training programs and all the respective interview results will be collated and compared. Direct quotes may be used in the thesis and publications where you can choose to be named or remain anonymous.

What are the potential risks of participating in this project?

There are no risks in participating in this study. You have no obligation to answer the questions posed and you can also choose to remain anonymous when the interview results are presented.

How will this project be conducted?

The interviews will be conducted privately in conjunction with swimming events where you may be attending or the student researcher will travel to a location which suits you better (at your request). Here, the interview will take place in the closest available meeting room to ensure privacy and confidentiality.

Who is conducting the study?

Victorian University / Swimming Australia

Chief Investigator:	Prof. Damian Farrow	+61 408 445 701
Student Researcher:	Victoria Brackley	+61 468 952 944

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

CONSENT FORM FOR PARTICIPANTS INVOLVED IN RESEARCH

INFORMATION TO PARTICIPANTS:

We would like to invite you to be a part of a study entitled '***Exploring the transfer from drills to skills in freestyle swimming'.***

The overarching aim of this PhD project is to examine the efficacy of freestyle swimming training drills in relation to the full freestyle swimming stroke. In order to evaluate the effectiveness of the existing learning environment, specifically that of elite freestyle swimmers, it is important to understand how you, as the coach, approach skill development. More specifically, this particular study aims to establish the most commonly practiced freestyle drills used by elite Australia coaches. You will be asked to participant in a once-off, private interview conducted in conjunction with swimming events where you may be attending or the student researcher will travel to a location which suits you better (at your request). Here, the interview will take place in the closest available meeting room to ensure privacy and confidentiality. Your contribution and input into this project will help put Australian swimming at the forefront in regards to developing even more effective training protocols which is planned to lead to even more success.

CERTIFICATION BY PARTICIPANT:

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

certify that I am at least 18 years old* and that I am voluntarily giving my consent to participate in the study entitled '***Exploring the transfer from skills to drills in elite freestyle swimming***' being conducted at Victoria University in partnership with Swimming Australia by:

Chief Investigator: Prof. Damian Farrow

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:

Student Researcher: Victoria Brackley

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

- A 60 min private interview (digitally recorded) with the student researcher, Victoria Brackley
- The interview results being collated by the student researcher, Victoria Brackley, in order to identify the most common freestyle drills used in elite Australian swimming.
- Direct quotations being used in the thesis and subsequent publications where I will remain anonymous (should you wish to be identified please mention this to the student researcher)

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: / /20

Any queries about your participation in this project may be directed to:

Chief Investigator: Prof. Damian Farrow +61 408 445 701

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

Appendix B: Participant information and consent forms (Chapter 4, 5 and 6)

INFORMATION TO PARTICIPANTS INVOLVED IN RESEARCH

You are invited to participate

You are invited to participate in a research project entitled **'Exploring the transfer from drills to skills in elite freestyle swimming'.**

This project is being conducted by a student researcher, Mrs. Victoria Brackley, as part of a PhD study at Victoria University (VU) in partnership with Swimming Australia (SAL). The PhD study is under the supervision of Prof. Damian Farrow and Dr. Kevin Ball from the College of Sport and Exercise Science | Institute for Health and Sport (IHES) at VU, Dr. Sian Barris from the South Australian Sports Institute (SASI) and Dr. Elaine Tor from the Victorian Institute of Sport (VIS).

Project explanation

The purpose of practicing skills in sport is to increase performance capability in competitive environments. Traditionally, drills are placed within the training environment to replicate adaptive movements and practice skills. It has been argued that many practice drills lack the capability to represent the behavioural and movement patterns required in the competitive environment. However, to date, there is a lack of research investigating this issue in swimming.

Consequently, the overarching aim of this project is to examine the efficiency of freestyle swimming training drills in relation to the full freestyle swimming stroke. More specifically, this study will investigate movement differences between practiced freestyle drills and the full freestyle stroke in both the training and competitive environment. Does the intension of the drill match the performance outcome?

To help understand the movement difference between the drills and swimming full freestyle, your technique (using video cameras) will be assessed while performing drills and swimming freestyle normally. This contribution will facilitate understanding the representativeness of drills and will help develop better training practice to give athletes that extra winning edge.

What will I be asked to do?

There is no obligation to participate in this study and there will be no unfair discrimination or ramification to the services you receive should you choose not to participate. Participation in this study is not related to selection / deselection in any of the National teams. It is voluntary to participate where you will not be reimbursed for your time or travel to the VIS. The data collected as part of this project will not be shared with SAL or any of the national sporting institutes (VIS). You will be requested to attend one session at the VIS indoor pool lasting approximately 120 minutes.

First, you will be asked to perform the single arm, long dog drill, polo and kicking drill (randomly ordered); and in the second session, you will be asked to perform a suited time-trial (short course). Before each session, you will have the opportunity to perform your usual pre-set or pre-competition warm-up. This warm-up period is estimated to be roughly 800 m in length where you will be asked not to perform any of the four drills to be assessed during this period. Before entering the water, joint / segment markers will be placed on your body. Once warmed up, you will be asked to perform the freestyle drill in a progression as 50 m drill followed by 50 m full freestyle, initiated from a push start. This sequence will be repeated three times (300 - 400m) before the next drill will be assessed. In total, you will be asked to swim 1400m.

For all sessions, joint / segment markers will be affixed to your body / swimsuit and your performance will be filmed using eight cameras (four above- and four below-water).

What will I gain from participating?

Participating in this study provides a unique opportunity to be part in an original research, conducted by a world-leading University in Sport Science. Furthermore, contribution and input into this project will help put Australian swimming at the forefront in regards to developing even more effective training protocols which is planned to lead to even more success.

Participating in this study may cause no direct benefit to swimming performance. However, once all the testing sessions are completed and the data has been processed, you will be provided with a detailed report relating to your freestyle technique. Additionally, you will receive a report on how representative the four freestyle drills trialled are to the full freestyle stroke.

How will the information I give be used?

The information collected in this study will be used by Mrs. Victoria Brackley for the purpose of completing a PhD thesis. Data will also be used for preparing journal articles for scientific publications and conference presentations by Mrs. Victoria Brackley. At no time will you be personally identified in the presentation of these results.

What are the potential risks of participating in this project?

There are physical risks involved in this project as you will be performing physical movements in the water during each of the two sessions. These risks are no more than those associated with a standard training session or when competing, mainly muscle soreness or fatigue and risk of slipping on tiles around the pool.

To minimise the risks of fatigue and concentration loss, the drills / freestyle swimming will be separated into 300 m blocks and you will be given the opportunity to take as many breaks as required between each 50 m swim in the drill or freestyle stroke. Furthermore, the testing setup will be secured to ensure no obstacles are in the way that could cause injury.

Should any physical risks occur, all sessions are held at the VIS – sports institute with sport doctors and physiotherapists, and you can be sent to a professional for medicine or advice. These sport doctors and physiotherapists are almost always at the VIS; nonetheless the testing sessions will be scheduled within times where support personnel are confirmed to be on-site.

You may feel concerned that their performance during the two sessions may negatively highlight physical or skill deficiencies. The researchers will reinforce that all data will remain strictly confidential with their names de-identified using codes.

How will this project be conducted?

To minimise inconvenience, the session could be positioned within a recovery session during the training week. The session procedures will consist of swimming 50m of drill followed by 50 m of freestyle swimming, initiated from a push start. This sequence will be repeated three times (300 - 400 m) before the next drill will be assessed. The total distance swam will be 14000 m of drill / swim plus the pre-set warm-up.

Joint / segment markers will be affixed to your body / swimsuit. The anatomical landmark joints include: right and left shoulder, elbow, wrist, hip, knee, ankle and heel bone. Additionally, markers will be place on the swimming cap, middle finger and big toe. The student investigator will place the markers on the joint / segment landmarks or with guided instructions from the student investigator, you may place the markers on yourself. The placement of the markers will occur before the warm-up and will be done inside the pool environment. Should you feel uncomfortable with this process, markers can be placed in a more private location where you may have a chaperon present. Eight cameras (four above- and four below-water) will be placed around the pool to film his / her performance. The analysis of the footages will allow the evaluation of your swimming technique. The footage and data will only be seen and analysed by the research team for research purposes.

Who is conducting the study?

This project is being conducted by VU, College of Sport and Exercise Science | IHES and SAL. Should you have any queries or for further information regarding this study and your participation, please contact the Damian Farrow or Victoria Brackley.

Chief Investigator
Prof. Damian Farrow
Damian.Farrow@vu.edu.au
+61 408 445 701

Student Investigator
Mrs. Victoria Brackley
victoria.brackley@live.vu.edu.au
+61 468 952 944

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INFORMATION TO PARTICIPANTS UNDER 18 INVOLVED IN RESEARCH

Your child is invited to participate

You child is invited to participate in a research project entitled **'Exploring the transfer from drills to skills in elite freestyle swimming'.**

This project is being conducted by a student researcher, Mrs. Victoria Brackley, as part of a PhD study at Victoria University (VU) in partnership with Swimming Australia (SAL). The PhD study is under the supervision of Prof. Damian Farrow and Dr. Kevin Ball from the College of Sport and Exercise Science | Institute for Health and Sport (IHES) at VU, Dr. Sian Barris from the South Australian Sports Institute (SASI) and Dr. Elaine Tor from the Victorian Institute of Sport (VIS).

Project explanation

The purpose of practicing skills in sport is to increase performance capability in competitive environments. Traditionally, drills are placed within the training environment to replicate adaptive movements and practice skills. It has been argued that many practice drills lack the capability to represent the behavioural and movement patterns required in the competitive environment. However, to date, there is a lack of research investigating this issue in swimming.

Consequently, the overarching aim of this project is to examine the efficiency of freestyle swimming training drills in relation to the full freestyle swimming stroke. More specifically, this study will investigate movement differences between practiced freestyle drills and the full freestyle stroke in both the training and competitive environment. Does the intension of the drill match the performance outcome?

To help understand the movement difference between the drills and swimming full freestyle, your technique (using video cameras) will be assessed while performing drills and swimming freestyle normally. This contribution will facilitate understanding the representativeness of drills and will help develop better training practice to give athletes that extra winning edge.

What will your child be asked to do?

There is no obligation to participate in this study and there will be no unfair discrimination or ramification to the services you receive should you choose not to participate. Participation in this study is not related to selection / deselection in any of the National teams. It is voluntary to participate where you will not be reimbursed for your time or travel to the VIS. The data collected as part of this project will not be shared with SAL or any of the national sporting institutes (VIS). Your child will be requested to attend one session at the VIS indoor pool lasting approximately 120 minutes each.

Firstly, your child will be asked to perform the single arm, log dog drill, polo and kicking drill (randomly ordered); next, your chile will be asked to perform a suited time-trial (short course). Before each session, your child will have the opportunity to perform his/her usual pre-set or pre-competition warm-up. This warm-up period is estimated to be roughly 800 m in length where your child will be asked not to perform any of the four drills to be assessed during this period. Following the warm-up, your child will have joint / segment markers place on their body. When back in the water, your child will be asked to perform the freestyle drill in a progression as 50 m drill followed by 50 m full freestyle, initiated from a push start. This sequence will be repeated six times (300 - 400 m) before the next drill will be assessed.

Secondly, your child will be asked to perform a suited time trial - swimming a 100 m time trial (short course). Wearing his/her race suit, you child will be asked to swim a set distance (100m), as fast as possible, against the clock.

For all sessions, joint / segment markers will be affixed to your child body / swimsuit and participant' performance will be filmed using eight cameras (four above- and four below-water). The anatomical landmark joints include: right and left shoulder, elbow, wrist, hip, knee, ankle and heel bone. Additionally, markers will be place on the swimming cap, middle finger and big toe.

What will your child gain from participating?

Participating in this study provides your child with a unique opportunity to be part in an original research, conducted by a world-leading University in Sport Science. Furthermore, contribution and input into this project will help put Australian swimming at the forefront in regards to developing even more effective training protocols which is planned to lead to even more success.

Participating in this study may cause no direct benefit to swimming performance. However, once all the testing sessions are completed and the data has been processed, your child will be provided with a detailed report relating to their freestyle technique. Additionally, your child will receive a report on how representative the four freestyle drills trialled are to the full freestyle stroke.

How will the information given be used?

The information collected in this study will be used by Mrs. Victoria Brackley for the purpose of completing a PhD thesis. Data will also be used for preparing journal articles for scientific publications and conference presentations by Mrs. Victoria Brackley. At no time will your child be personally identified in the presentation of these results.

What are the potential risks of participating in this project?

There are physical risks involved in this project as your child will be performing physical movements in the water during the session. These risks are no more than those associated with a standard training session or when competing, mainly muscle soreness or fatigue and risk of slipping on tiles around the pool.

To minimise the risks of fatigue and concentration loss, the drills / freestyle swimming will be separated into 150 m blocks and you will be given the opportunity to take as many breaks as required between each 25 m swim in the drill or freestyle stroke. Furthermore, the testing setup will be secured to ensure no obstacles are in the way that could cause injury.

Should any physical risks occur, all sessions are held at the VIS – sports institute with sport doctors and physiotherapists, and you can be sent to a professional for medicine or advice. These sport doctors and physiotherapists are almost always at the VIS; nonetheless the testing sessions will be scheduled within times where support personnel are confirmed to be on-site.

You may feel concerned that your child's performance during the session may negatively highlight physical or skill deficiencies. The researchers will reinforce that all data will remain strictly confidential with their names de-identified using codes.

How will this project be conducted?

To minimise inconvenience, the first session could be positioned within a recovery session during the training week. The session procedures will consist of swimming 50m of drill followed by 50 m of freestyle swimming, initiated from a push start. This sequence will be repeated three times (300 - 400 m) before the next drill will be assessed. The total distance swam will be 1400 m of drill / swim plus the pre-set warm-up.

Joint / segment markers will be affixed to your child body / swimsuit. The anatomical landmark joints include: right and left shoulder, elbow, wrist, hip, knee, ankle and heel bone. Additionally, markers will be place on the swimming cap, middle finger and big toe. The student investigator will place the markers on the joint / segment landmarks or with guided instructions from the student investigator, your child may place the markers on yourself. The placement of the markers will occur before the warm-up and will be done inside the pool environment. Should your child feel uncomfortable with this process, markers can be placed in a more private location where your child may have a chaperon present. Eight cameras (four above- and four below-water) will be placed around the pool to film his / her performance. The analysis of the footages will allow the evaluation of your child's swimming technique. The footage and data will only be seen and analysed by the research team for research purposes.

Who is conducting the study?

This project is being conducted by VU, College of Sport and Exercise Science | IHES and SAL. Should you have any queries or for further information regarding this study and your participation, please contact the Damian Farrow or Victoria Brackley.

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Damian.Farrow@vu.edu.au
+61 408 445 701

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CONSENT FORM FOR PARTICIPANTS INVOLVED IN RESEARCH

INFORMATION TO PARTICIPANTS

We would like to invite you to be a part of a study entitled **'Exploring the transfer from drills to skills in freestyle swimming'.**

The overarching aim of this PhD project is to examine the efficiency of freestyle swimming training drills in relation to the full freestyle swimming stroke. In order to evaluate the effectiveness of the existing learning environment, specifically that of elite freestyle swimmers, we would like to assess your swimming technique over two sessions when performing the freestyle drill and full freestyle stroke. Your contribution and input into this project will help put Australian swimming at the forefront in regards to developing even more effective training protocols which is planned to lead to even more success. Should you choose not to participate in this study, there will be no impact on the relationship or services / support provided by Swimming Australia or your national sporting institution.

CERTIFICATION BY PARTICIPANT

I, ____(participant's name)

certify that I am at least 18 years old and that I am voluntarily giving my consent to participate in the study entitled **'Exploring the transfer from drills to skills in freestyle swimming'** being conducted at Victoria University in partnership with Swimming Australia.

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 Mrs. Victoria Brackley and that I freely consent to participation involving the below mentioned procedures:

- Attending testing session held at the Victorian Institute of Sport (VIS);
- Joint / segment markers placed on body / swimsuit;
- Performance of four freestyle drills where each drill will be performed separately in a 300 - 400 m progression of 50 m drill followed by 50 m of full freestyle;
- Assessment for freestyle drill and swimming technique via video analysis; and,
- Being filmed during two swimming sessions where the footage will only be seen and analysed by the research team for the research purpose.

I agree with the all of the above procedures to be undertaken during this research project

☐ Yes ☐ No (please tick)

I agree to being further contacted to participate in the intervention study proceeding this research project

☐ Yes ☐ No (please tick)

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.

Participant signed:____ Date: _____________

Any queries about your participation in this project may be directed to Damian Farrow (Chief Investigator) or Victoria Brackley (Student Investigator) listed below:

Chief Investigator
Prof. Damian Farrow
Damian.Farrow@vu.edu.au
+61 408 445 701

Student Investigator
Mrs Victoria Brackley
victoria.brackley@live.vu.edu.au
+61 468 952 944

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

CONSENT FORM FOR PARTICIPANTS UNDER 18 INVOLVED IN RESEARCH

INFORMATION TO PARTICIPANTS

We would like to invite your adolescent to be a part of a study entitled **'Exploring the transfer from drills to skills in freestyle swimming'.**

The overarching aim of this PhD project is to examine the efficiency of freestyle swimming training drills in relation to the full freestyle swimming stroke. In order to evaluate the effectiveness of the existing learning environment, specifically that of elite freestyle swimmers, we would like to assess your swimming technique over three sessions when performing the freestyle drill and full freestyle stroke. Contribution and input into this project will help put Australian swimming at the forefront in regards to developing even more effective training protocols which is planned to lead to even more success. Should you choose not to participate in this study, there will be no impact on the relationship or services / support provided by Swimming Australia or your national sporting institution.

CERTIFICATION BY PARTICIPANT

I, ____ (parent/guardians name)

of ____ (parent/guardian's suburb)

certify that I am at least 18 years old and that I am voluntarily giving my consent for

____ (participant/child's name)

to participate in the study entitled **'Exploring the transfer from drills to skills in freestyle swimming'** being conducted at Victoria University in partnership with Swimming Australia.

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 Mrs. Victoria Brackley and that I freely consent to my adolescent's participation involving the below mentioned procedures:

- Attending testing session held at the Victorian Institute of Sport (VIS);
- Joint / segment markers placed on body / swimsuit;
- Performance of four freestyle drills where each drill will be performed separately in a 300 - 400 m progression of 50 m drill followed by 50 m of full freestyle;
- Assessment for freestyle drill and swimming technique via video analysis; and,
- Being filmed during two swimming sessions where the footage will only be seen and analysed by the research team for the research purpose.

I agree with the all of the above procedures to be undertaken during this research project

☐ Yes ☐ No (please tick)

I agree to being further contacted to participate in the intervention study proceeding this research project

☐ Yes ☐ No (please tick)

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.

Parent / guardians signed:____ Date: ______________

Participant signed:____ Date: ______________

Any queries about your participation in this project may be directed to Damian Farrow (Chief Investigator) or Victoria Brackley (Student Investigator) listed below:

Chief Investigator
Prof. Damian Farrow
Damian.Farrow@vu.edu.au
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Student Investigator
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