Technical factors affecting speed fluctuations and performance in the underwater phase of breaststroke

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PhD 2023

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A thesis submitted in partial fulfilment of the requirements of Manchester Metropolitan University for the degree of Doctor of Philosophy

Department of Science and Engineering
Manchester Metropolitan University in collaboration with British Swimming

2023

Abstract

Elite swimming races are usually decided by small margins, with the start and turn often being key determinants of race success. This thesis focuses on the underwater phase of the breaststroke start and turn. The first study used data from international competitions to illustrate that GB breaststrokers have room for improvement in their starts and turns, compared to international competitors. This was followed by a series of experimental studies utilising three-dimensional video to analyse the breaststroke underwater phase (BUP) techniques used by elite and sub-elite GB swimmers.

Participants differed in when they performed the fly kick within the BUP with the majority adopting the separated technique, where the fly kick was initiated and completed prior to Pull-down. In this group, time spent performing the breaststroke kick was the only temporal metric to correlate strongly with BUP performance (10 m time). Significant differences between elite and sub-elite swimmers were found in durations of Arm recovery and Arm to leg recovery.

Correlations were found between BUP performance and mass centre velocity variables in the Fly kick preparation, Pull-down, Glide 2 and Arm + leg recovery phases. Breakout distance, Fly kick preparation phase distance, Arm + leg recovery end of phase distance and Arm + leg recovery minimum velocity distance all correlated strongly with BUP performance.

Elite swimmers showed significantly higher mean velocities than sub-elite during the propulsive phases of the Pull-down and Kick, and the Arm + leg recovery. They travelled significantly further underwater during the complete BUP and during the Fly kick prep/recovery, Fly kick upbeat, and Arm + leg recovery phases. Pull-down hand speed correlated strongly with BUP performance for the combined cohort and was higher in the elite than the sub-elite group.

The thesis concludes by reporting a five-year technical intervention with a World leading breaststroker. The work demonstrated that through multiple, interdisciplinary interventions, positive changes in performance can be effected: the elite breaststroker reduced his breaststroke start time by 0.26 s.

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Acknowledgements

I would like to thank my supervisory team for their guidance and unwavering support throughout my studies, for me there were no better people in Swimming Biomechanics than Professor Carl Payton and Oliver Logan. Professor Carl Payton has gone above and beyond with his level of support, patience and guidance which has enabled me to grow and develop as a researcher, practitioner and person throughout the completion of my PhD. Olly Logan, has been a huge reason why I have had the ability to complete this PhD, whether that being by academic guidance, reducing the British Swimming work load or just being a friend and a person to listen.

Thank you to British Swimming coaches Mel Marshall and Dave Hemmings and the rest of the Sports Science and Sports Medicine Team. You have either practically helped me with data collections or emotionally supported me throughout the PhD. You have all pushed and developed me to be the best practitioner I can be.

Without question there is no way I feel I would have been able to complete this PhD without Victoria Jones. From the origin of our PhDs and roles within British Swimming we have been two halves of a whole. Her unwavering belief in me and my ability, the encyclopaedic knowledge of all things grammatical and statistical she poses and the consistent presence of an ear to listen has elevated this journey above what I imagined and I know I have a friend for life.

To my Mum, Dad, Sister and girlfriend Milly. You have supported me throughout the ups and downs, the “I can’t do its” and the “can I just talk you through this?". The love and care you show me every day has made me into the person I am today and has made me believe that I would get through the downs, that I could do it and it was possible.

I love you all.

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Abbreviations

BUP – Breaststroke Underwater Phase

CoM – Centre of Mass

GB – Great Britain

FINA – Fédération Internationale de Natation

IMUs – Inertial Measurement Units

PB – Personal Best

CFD – Computational Fluid Dynamics

SWC – Smallest Worthwhile Change

SDC – Smallest Detectable Change

SEM – Standard Error of Measurement

3D – Three-dimensional

2D – Two-dimensional

SPM – Statistical Parametric Mapping

RMSE – Root Mean Square Error

MANOVA – Multivariate Analysis of Variance

C_D – Coefficient of drag

C_L – Lift Coefficient

F_D – Drag Force

F_F – Friction Drag

F_P – Form Drag

F_W – Wave Drag

A – Acceleration

IM – Individual Medley

IOC – Internal Olympic Committee

SL – Stroke Length

DPS – Distance per Stroke

SR – Stroke Rate

GPS – Global Positioning System

NGB – National Governing Bodies

EIS – English Institute of Sport

CV – Coefficient of Variation

FFT – Fast Fourier Transformation

MMU – Manchester Metropolitan University

LOA – Limits of Agreement

VIV Index – Index of Variation of Intra-cyclic Velocity

UDK – Underwater Dolphin Kick

CMJ – Counter Movement Jump

1 Chapter One: Introduction

1.1 Overview

The aim of this chapter is to provide a brief introduction to the sport of swimming and then to explain the importance of breaststroke starts and turns, specifically the underwater phase. The concluding section of the chapter details the academic aims and objectives of the PhD and details the structure of the thesis.

1.2 Area of study

1.2.1 Swimming

Swimming is characterised by the interaction of propulsive and resistive forces (drag) in the water. The aim of the swimmer is to maximise the propulsive forces to overcome the drag throughout a race. Both maximising propulsion and reducing drag can contribute to the improved performance of a swimmer (Figueiredo *et al*., 2012; Zhan *et al*., 2014). Olympic swimming has consisted of four different strokes; freestyle, backstroke, butterfly and breaststroke, since 1956. The 400 metres (m) individual medley (400 IM) (which includes all above strokes in the order: butterfly, backstroke, breaststroke and freestyle) has also been included in the Olympics for both genders since 1964, with the 200m individual medley being included from 1968 and 1972 for male and female swimmers, respectively (Swim England, 2022). Through the inclusion of new technology (body suits), greater research into swimming training methods and rule changes (inclusion of a single dolphin kick to the breaststroke underwater phase) performances and World Records have continued to progress. An example is the progression in the Men’s 100 m breaststroke long course (50 m pool) from the first World Record being set at 1 minute, 11 seconds and 40 milliseconds in 1961 to breaking the 1-minute barrier in 2001 (59.97 s). It currently sits at 56.88 s, which was achieved in 2019 and represents the only male to achieve a sub 57 second 100 m breaststroke performance (FINA, 2022). Additionally, the World Record for 100 m breaststroke short course (25 m pool) is currently 55.28 s, which is considerably faster than the long course record, thus highlighting the importance of turns performance.

Many World Records were established by swimmers wearing bodysuits which were allowed in competition from February 2008 until December 2009, with the 200 m freestyle men's and women's and women's 200 m butterfly World Records still standing from 2009. The men's 100 m freestyle World Record set in 2022, is the first time this record has been broken since the use of the body suits in 2009.

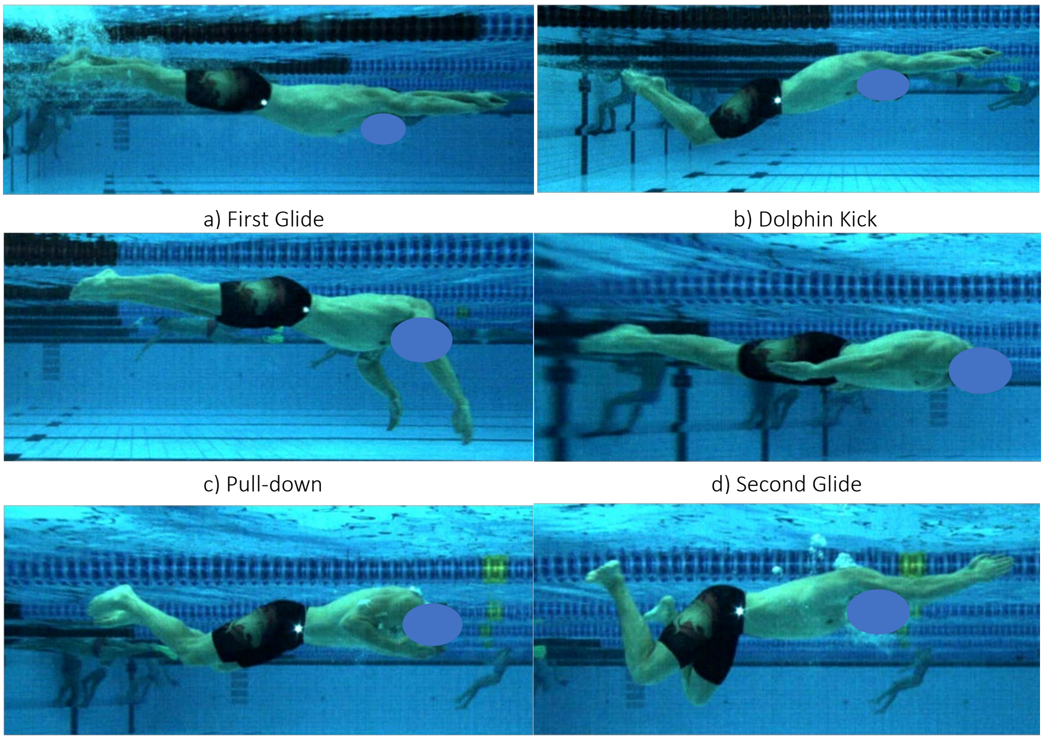
Elite swimmers and coaches constantly challenge themselves to improve performance from a physiology, strength and conditioning, psychological or technical standpoint. Swimming fast is essential when competing against the top swimmers in the world. In the 200m breaststroke at the 2016 Olympic Games, the difference between 3rd and 4th was 0.08 s. These small gains that swimmers can achieve are often the difference between medalling and not.

1.2.2 Starts and turns

A swimming race is often broken down into four components: the start; turns; free swimming and finish. Swim start and turn performance has frequently been associated with overall race performance (Cossor and Mason, 2001). Start time is usually defined as the time from the start signal to the swimmer's head reaching the 15 m line. It contributes to between 0.8 to 26.1% of the total race time, depending on distance of the race and the stroke being performed, with the underwater phases having the greatest influence (Cossor and Mason, 2001).

1.2.3 Breaststroke underwater phase (BUP)

Following a dive entry off a start and a wall push-off from a turn a swimmer is permitted to complete one arm stroke completely back to the legs (Pull-down), a dolphin kick prior to the first breaststroke kick, one breaststroke kick and begin the second arm pull before surfacing (Figure 1). Prior to 2005, breaststroke swimmers were not allowed a dolphin kick; however, following the controversy of swimmers completing a dolphin kick off both start and turns, which were not visible from the surface, FINA (Fédération Internationale de Natation; the international swimming federation for water sports) made a rule change. To prevent this from illegally happening, in 2005 a single dolphin kick was allowed once the hands had started to separate. In 2014, FINA further amended this rule to permit a single dolphin kick at any point prior to the first breaststroke kick (Figure 1.1).



a) First Glide b) Dolphin Kick c) Pull-down d) Second Glide e) Arm and Leg Recovery f) Kick

Figure 1.1: Underwater Sub Phases of the Breaststroke Underwater Phase (BUP). a) 1st Glide – Time between toe immersion/toes leaving the wall and beginning of hand separation/initiation of the dolphin kick, b) Dolphin Kick – Time between the initiation of the upbeat and end of the downbeat, c) Pull-down – Time between beginning of hand separation to end of backward movement of hands relative to the body, d) 2nd Glide – Time between end of Pull-down to beginning of forward movement of hands relative to body, e) Arm and leg recovery – Time between end of 2nd glide to first backward movement of feet relative to body, f) Kick – Time between end of Leg recovery to the in sweep of the feet that occurs after the knees have extended fully.

Swimming underwater has an advantage to swimming on the surface, due to a reduction in resistance from surface waves. Specifically, within breaststroke races, performing a full arm stroke (Pull-down) underwater can be beneficial, but to maintain a high underwater velocity, the BUP must be carefully coordinated and practised to maximise its contribution to 15 m (start time) and overall race performance (Seifert *et* *al*., 2007). Attention should also be paid to the hydrodynamic streamline position specifically in the first glide, and the minimisation of the time spent in the second glide (Figure 1.1) (Vilas-Boas *et al*., 2010). Technical improvements made to any element of the underwater phase should reduce overall start time. Despite this, to date, breaststroke research is heavily weighted towards the free-swimming element of the race, specifically coordination, and the use of video analysis or inertial-magnetic measurement units (IMU) to assess 3D joint kinematics and cyclic pattern recognition. Research on the underwater phase of the start or turn in breaststroke is extremely limited.

Biomechanical analysis of the BUP has only been completed by three groups of researchers (Seifert *et al*., 2007; Seifert *et al*., 2021; Gonjo and Olstad, 2021), with no research being completed to date using 3D kinematic analysis of a full-body swimmer model for the entire breaststroke underwater phase. Additionally, the Seifert *et al*. (2007) research was completed prior to the rule change where the inclusion of a dolphin kick was allowed at any point prior to the breaststroke kick in 2014 and so does not incorporate the dolphin kick.

1.2.4 Breaststroke Co-ordination patterns

The BUP involves considerable speed fluctuation, with the swimmer typically experiencing three speed peaks created during the propulsive phases, in addition to two velocity minima associated with the glide and recovery phases. The challenge to the swimmer is to adopt timings and technique to increase propulsion when the instantaneous velocity decreases below the mean swimming velocity, and to glide when the instantaneous velocity is above the mean swimming velocity (Seifert *et al*., 2007). To achieve this, breaststroke swimmers use a variety of techniques. McCabe *et al.* (2022) identifies that elite breaststrokers perform one of three BUP techniques which differ with respect to the timing of the dolphin kick: the fly-kick first technique (fly-kick is initiated and completed prior to Pull-down); the combined technique (Pull-down is initiated before the fly-kick is complete, consequently an overlap of phases is observed); the Pull-down first technique (Pull-down is completed prior to fly-kick). Seifert *et al.* (2021) identified three similar coordination profiles, namely: “Continuity”; “Glide” and “Superposition”, with both the continuity and glide profiles being included in the fly-kick first technique of McCabe *et al*. (2022). Although research has been conducted into this area in both the competition (McCabe *et al*., 2022) and training environment (Seifert *et al.,* 2021), a gap potentially exists for a greater of number of elite swimmers to be profiled in a training environment with underwater cameras present to enable the accurate identification of techniques used by a larger sample size.

1.3 Study rationale

The outcomes of swimming races are often decided with such small margins that the ability to improve start or turn performance could be the determining factor of race success. The majority of swimming biomechanics research has been completed on the freestyle technique, with relatively little research completed on the other strokes including breaststroke free swimming. Even less research has been conducted on the underwater phase of the breaststroke start and turn. Therefore, this thesis will contribute to the limited body of knowledge on the breaststroke underwater technique and inform the practice of coaches and practitioners to develop GB breaststrokers' underwater ability.

As a nation, Great Britain has several world class breaststrokers, some of whom have won medals on the world stage. However, as stated above breaststroke events are rapidly progressing and the requirement to continue on this trajectory is essential.

With the ability to improve the technical components of the underwater phase following both a start and turn, changes in kinematic parameters to increase propulsion and reduce drag could reduce the swimmer's time to 15 m and consequently increase the chance of GB breaststrokers being successful at future major competitions. The proposed research will be the first to provide a full kinematic analysis of the BUP involving a detailed analysis of its sub-skills/sub-phases which will contribute to the technical improvement of GB breaststrokers.

1.4 Academic Aims and Objectives

Aims

The aims of this thesis were to:

- Identify the technical factors affecting speed fluctuations and performance in the underwater phase of breaststroke;
- Provide evidence-based information on key technical factors of the BUP that can be utilised by coaches and practitioners to improve performance.

Objectives

The objectives of this thesis were to:

- Establish the relative difference between GB and international breaststrokers for the free swimming and start and turn race components to reveal the relative strengths and weaknesses of GB breaststroke swimmers;
- Establish the validity of three methods of obtaining instantaneous speed of the BUP (3D CoM, 3D mid-hip and speed reel);
- Determine whether temporal, CoM speed and 3D kinematic differences exist between elite and sub-elite swimmers for the BUP;
- Determine, through the use of a case study, whether an intervention using established critical determinants of a BUP can improve performance.

1.5 Chapter organisation

The remainder of this thesis comprises eight chapters: a review of literature; a preliminary experimental study; a general methods section; four experimental studies; a case study and a summary, applications and recommendations chapter.

Chapter 2 is a review and critique of the literature surrounding swimming starts and turns, specifically breaststroke starts and turns, the analysis of the breaststroke underwater phase including components, speed fluctuations and joint and limb kinematics. Additional areas include a brief summary on drag, the relationship between drag and performance and measuring speed in an aquatic environment.

Chapter 3 presents a descriptive study using race analysis data to determine the strength of association between breaststroke swimmers' start and turn times and overall race time in each breaststroke event, to highlight the importance of start and turns in a breaststroke race. Additionally, the study aims to establish the relative difference between GB and international breaststrokers for the free swimming and start and turn race components to reveal the relative strengths and weaknesses of GB breaststroke swimmers.

Chapter 4 General Methods includes information on participants, data collection methods, equipment, calibration of equipment and ethical considerations including recruitment, informed consent, anonymity and confidentiality for the majority of the thesis. Additionally, specific procedures undertaken for studies 3, 4, and 5 including experimental protocol, digitising and data processing are included.

Chapter 5 is a method-based chapter evaluating the differences between three methods of collecting and measuring speed within the aquatic environment. Specifically, it compares the CoM speed obtained through 3D video analysis to that of the speed derived from a fixed point of the hip and a 'speed reel' system speed output, for the BUP.

Chapter 6 presents a study focusing on the temporal analysis of the BUP. The aim of this study is to examine whether timings differ in the BUP performed following a wall push and following a dive start, and to identify differences between the BUP temporal characteristics of elite breaststroke specialists and sub-elite swimmers.

Chapter 7 further analyses the BUP through CoM velocities and trajectories of elite and sub-elite breaststrokers. The aims of this study are to establish if differences exist in the CoM trajectories or CoM speed profiles of elite and sub-elite breaststroke swimmers and to examine the relationships between CoM trajectories, speeds and performance.

Chapter 8 is a full 3D kinematic analysis of the BUP, examining associations between variables and performance. This study aims to identify key variables that differ between elite and sub-elite samples and to provide evidence as to what mechanisms yield high level performance.

Chapter 9 is a case study focusing on an elite breaststroker over the extended 5-year Olympiad, examining start and BUP interventions that were introduced and the impact they had on start and turn performance.

Chapter 10 contains general conclusions, recommendations, limitations and suggestions for future studies.

2 Chapter Two: Literature Review

2.1 Brief Introduction to swimming

Swimming became an Olympic sport in 1896 with solely freestyle (front crawl) and breaststroke events. Backstroke was later added in 1904 and with the creation of butterfly from an illegal breaststroke technique in 1956, the four Olympic strokes were established (British Swimming, 2020). Although the same four strokes have been present in competition since 1956, changes to the number of events based on distance and the addition of women's swimming in 1912, have continued to develop the Olympic swimming programme. Since 1996, the men and women's Olympic programmes have been almost identical, containing the same number of events, however over 400 m the women only competed in the 800 m freestyle, whilst the men only competed in the 1500 m freestyle. This disparity was only present pre 2021 in the Olympics, as women race in the 800 m and the 1500 m in all other major competitions including the World Championships. This disparity is no longer present as both genders race all distances (IOC, 2020).

The 400 m individual medley (400IM), which includes all above strokes in the order: butterfly; backstroke; breaststroke and freestyle has also been included in the Olympics for both genders since 1964, the 200 m individual medley being included from 1968 and 1972 for male and female swimmers respectively (History of Individual Medley | Olympic Swimming Strokes Explained, 2022).

Throughout a major competition, such as Olympics, World Championships and European Championships, a swimmer usually competes in a heat, semi-final and final. The fastest 16 and 8 swimmers progress from the heats into the semi-finals and from the semi-finals into the finals. However, in events where the distance covered is greater than 400 m only heats and finals are swum with the 8 fastest swimmers progressing into the final. Elite swimming, like all professional sports, is highly competitive, with Olympic and World records being broken on a regular basis (Morais *et al*., 2018). The ability to break these records is achieved through swimmers and coaches continuously challenging themselves to optimise performance and striving for the smallest gains and gradual improvements over time (Mooney *et al*., 2015).

Although aerobic (endurance) and anaerobic (speed) physiological changes are worked towards within each training cycle, the improvement of skills is an area of potential larger improvement. In the 2016 Olympic Games, 4th place in the 200 m men's breaststroke lost by 0.08 s, highlighting how very small margins decide the outcome of races. This demonstrates the necessity for making improvements in starts, turns and finishes.

2.2 Performance Model of Swimming

Swimming is characterised by the interaction of propulsive and resistive forces (drag). The aim of the swimmer is to maximise the propulsive forces to overcome the resistive forces (drag) throughout a race. Both maximising propulsion and reducing drag can contribute to the improved performance of a swimmer (Figueiredo *et al*., 2012; Zhan *et al*., 2014). To monitor swimmers throughout their career, to learn more about the strategies used by elite swimmers and to explore how the best in the world have the ability to win with such small margins, race analysis is now completed by many national swimming governing bodies at all major international competitions, including British Swimming.

In addition to applied race analysis, researchers such as Kjendlie *et al.* (2006) and Morais *et al.* (2018) have further studied the components of a race. Within this race analysis, a swimming race is often broken down into four components: the start; turns; free-swimming and finish (Figure 2.1). Although the definition of these race segments is consistent, the key distances often differ when determining the performance of starts and turns. These studies define start time as the period from the starting signal (gun time) to the swimmer's head reaching 15 m. Based on FINA's ruling that in all freestyle, backstroke and butterfly events the swimmer must breakout (resurface) before 15 m; 15 m has been highlighted as an ideal distance for defining start performance (Cossor and Mason, 2001a). However, there is a lack of consensus when measuring turn time. Some researchers, such as Mason and Cossor (2001b) define turn time as 7.5 m into the wall and 7.5 m out of the wall; others have used the time taken from 5 m into the wall until 10 m out of the wall (Kjendlie *et al*., 2006; B. R. Mason *et al*., 2015).

Recent studies have solely looked at gun time to 15 m and 5 m in to 15 m out for the start and turn determinant of performance, respectively (Morais *et al*., 2018; Veiga and Roig, 2017). These distances are those used within British Swimming's race analysis and will be consistently used within this thesis. In addition to overall start and turn performance being monitored, British Swimming now further breaks down the start and turn underwater segments by highlighting when each underwater segment of a start or turn is completed, building a database showing how long each swimmer takes within the underwater phases. For example, in breaststroke identifying when a swimmer performs their fly kick or Pull-down. Finish time is taken from the last 5 m into hand touch on the wall. Depending on the distances used to define the start and end of a start/turn, free-swimming is considered the remainder of the race (Figure 2.2). Metrics such as stroke length (SL), distance per stroke (DPS), stroke rate (SR) and velocity for segments throughout the race are calculated throughout the free-swimming phase of a race. Based upon the existing deterministic models in the literature, new models were developed for the purposes of the PhD/report that also encompass the Breaststroke Underwater Phase (BUP) and dolphin kick (Figures 2.5 and 2.6).

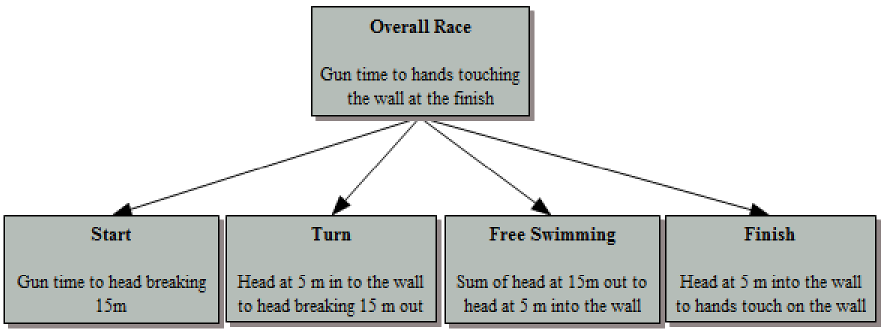


Figure 2.1: Deterministic Model of a Swimming Race (Based on Morais et al. 2018).

2.3 Temporal analysis research on starts and turns

Mason and Cossor (2000) found that the free-swimming component of a race had the strongest correlation to overall race time in all freestyle, backstroke, butterfly, breaststroke and individual medley events with a significance of <.01 for all except the women's 100m breaststroke which was still moderately correlated to race time with a significance of <.05. This is expected as free-swimming is the largest component of a race. However, the second highest correlation in all events was found to be turn time, which was shown to be strongly significantly correlated to overall race time in 92% of the races analysed. Although not identified by Mason and Cossor (2000), this was due to the inclusion of the 50 m freestyle which does not include a turn within long course swimming.

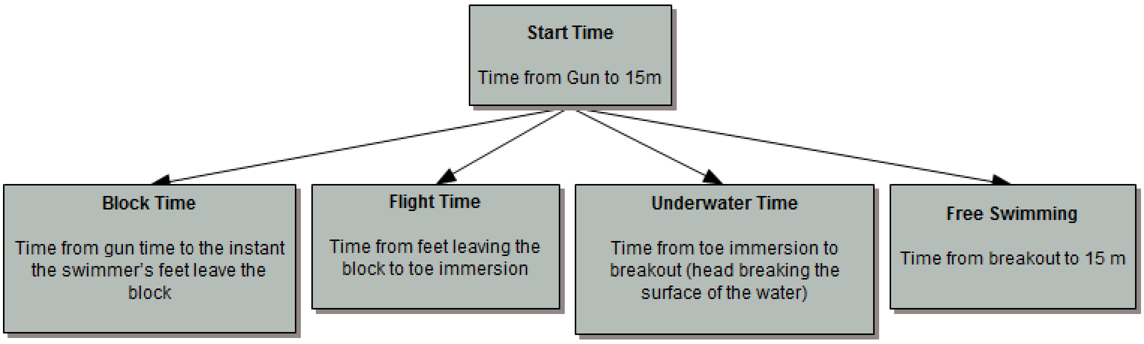


Figure 2.2: Deterministic Model of a Start (Based on Tor et al. 2014).

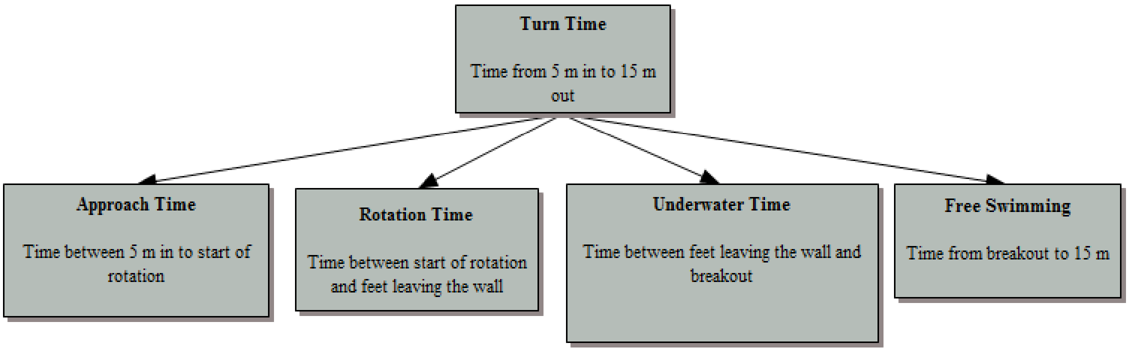


Figure 2.3: Deterministic Model of a Turn (Based on Morais et al. 2018).

Swim start and turn performance has frequently been associated with overall race performance, with start time (Figure 2.2) being found to contribute to between 0.8% and 26.1% of total race time, depending on the race distance and stroke used, and with the underwater phases having the greatest influence (Cossor and Mason, 2001). In sprint events such as the 100 m, start performance can account for 11-12% of race time and turning between 19-20%. In total, this can account for 31-32% of the overall race. Mason and Cossor (2000) found at the 1999 Pan Pacific Swimming Championships that there was a significant correlation between race result and start time in all freestyle events for men ($r = .50 – .87$), and all races ($r = .68 – .84$) excluding the 200 m freestyle and 800 m freestyle for females. Within the same study Mason and Cossor (2000) found a significant correlation between turn time (Figure 2.3) and race result for all freestyle events (r= .62 – .96), all 100 m and 200 m butterfly (r= .78 – .88), backstroke (r= .74 – .89) and breaststroke events (r= .53 – .91). The number of turns increases as event distance increases from short-distance to middle-distance and long-distance events, with 15 turns in the 800 m freestyle. Consequently, with the number of turns increasing, an improvement in turns could greatly affect overall race time, with just a 0.1 s improvement in each turn contributing to a 1.5 s improvement in overall race time in the 800 m freestyle (Morais *et al*., 2018).

2.3.1 Starts

Most swimmers in freestyle, breaststroke and butterfly events use a track start. A track start consists of a split stance with one foot placed on the rear wedge of the starting block and the front foot placed at the front. Once the gun signal is heard the swimmers drive into the water in a streamline position. In backstroke, a backstroke start is completed from the water. The swimmer's hands hold onto a grab-bar that is mounted on the starting block and a foot ledge is hung off the block at varying depths depending on the swimmer's preference. From here, the swimmers lift themselves out of the water and once the gun signal is heard, dive backwards to enter the water in a streamline position. Due to start performance having such an impact on overall race time, many researchers have studied starts (Seifert *et al*., 2007; Mason and Cossor, 2000; Cossor and Mason, 2001). Research has been conducted into the temporal aspects of a start, focusing on the contribution of the sub phase durations: reaction time; block time; flight time and underwater time (Tor *et al*., 2014).

Focusing specifically on the above water phases, Tor *et al.* (2015) found that take-off horizontal velocity and time spent on the block were key parameters to start performance. Vantorre *et al*. (2010) and Breed and Young (2003) also confirmed the importance of horizontal velocity with the addition of a short reaction time; however, they added the caveat that the movement on the block must be quick but be sufficient to maximise the impulse to provide a high horizontal velocity.

The block phases strongly influence the flight phase as the greater the horizontal velocity at take-off, the flatter the aerial trajectory will be, resulting in a shortened flight time. Consequently, Ruschel *et al*. (2007) and Tor *et al*. (2015) found no correlation between flight time and start performance. However, they found contradictory results on flight distance correlation with Ruschel *et al*. (2007) confirming a correlation yet, Tor *et al*. (2015) did not. On further inspection into Ruschel *et al*. (2007), the study included a minimal participant number (n=4) in comparison to Tor *et al*. (2015) (n=52) and therefore could be presenting a false positive. Although Ruschel *et al*. (2007) mentioned that Cossor and Mason (2001) found a significant correlation in flight distance, this was only in the 200 m and 400 m individual medley races, whereas shorter races were related to quicker and shorter entries to allow for a quicker time to 15 m. This limited evidence does not provide sufficient support for Ruschel *et al*. (2007).

Using competition data from the Sydney 2000 Olympic Games, Cossor and Mason (2001a) used simple correlational analysis to determine the relationship of the sub phases with start time. They found that although the preceding phases to the underwater phase all contributed to start performance in the Women's 100 m breaststroke, the underwater phase had the greatest influence on time to 15 m. When considering all strokes, they found a significant positive correlation with start time in underwater distance, underwater time and underwater velocity in 9 out of 14 races for both men and women (r= .60 – .94). Guimaraes and Hay (1985) also concluded that the underwater phase, specifically the glide time (time between water entry and commencing kicking), was more important than block or flight time; it was found to account for 94% variance in the starting time. The mean underwater velocity was specifically found to be significantly correlated (r= -.84) to starting time (time to 15 m).

2.3.2 Turns

In freestyle and backstroke events a tumble turn is performed by the swimmer. This consists of the swimmer rotating in a forward somersault-like manner to plant both feet on the wall (Slawson *et al*., 2010). In breaststroke and butterfly events the swimmer utilises an open turn which is defined as a simultaneous hand touch on the wall followed by a foot contact period (Slawson *et al*., 2010). Using the same competition data from the Sydney 2000 Olympic Games, Cossor and Mason (2001b) also researched into the temporal analysis of a turn, pre-turn velocity, in time (7.5 m to wall touch), out time (wall touch to 7.5 m), underwater distance, underwater time and underwater velocity. In this study Cossor and Mason (2001b) also used a Pearson's product correlation to determine the relationship between these variables and turn time. They found that for both genders, the underwater distance and time were significantly correlated to the turn time in backstroke, breaststroke and butterfly (underwater distance r= .50 – .88 and underwater time r= .48 – .87). These results were mirrored in research by Veiga *et al.* (2014a), stating that higher level swimmers travel for longer and further out of a turn in all strokes bar freestyle and therefore highlight that the extension of the underwater segment for swimmers in the above strokes could improve their turn time and overall race time by 0.1-0.2s, depending on the event. Although underwater time and distance have been found to be key variables in butterfly turn performance, significant correlations (P= <.02) between foot contact and push off speed have also been highlighted for international swimmers in comparison to national level (Tourny-Chollet *et al*., 2002). This research highlighted that a European champion used in the study had a reduced wall contact time and a greater speed off the wall than national level swimmers, however the proportion of contact time to total turn time was not significant, therefore showing that the international swimmer had an overall quicker turn and consequently a shorter wall contact time. Although the principle to generate a larger impulse is to apply a large force over a longer wall contact time (Araujo *et al*., 2010), the longer the time spent on the wall the longer the overall turn time would be and consequently could be negative to performance (Puel *et al*., 2012). Therefore, the strategy that many elite swimmers take is to reduce the contact time and consequently reduced their turn time instead of maximising impulse and push off force (Puel *et al*., 2012).

With underwater velocity, distance and time being highly correlated to start and turn performance the importance of this phase is emphasized. It highlights that if a swimmer wishes to improve their starts or turn performance then the underwater segment of both skills should be analysed and focused on.

2.4 The Breaststroke Underwater Phase (BUP)

The breaststroke underwater phase differs considerably from that used in the other three strokes. Breaststroke swimmers are only permitted to complete one arm stroke completely back to the legs, one dolphin kick prior to the first breaststroke kick, one breaststroke kick and begin the second arm pull before surfacing (FINA SW 7.1), in addition to completing two different glide phases; when competing in the three other strokes, swimmers are permitted to complete unlimited undulating movements underwater providing they surface before reaching 15 m (Figure 1.1 and 2.4). Breaststroke is the only stroke where a swimmer does not have to break the surface into their free-swimming section of the race before 15 m.

Breaststroke has had several rule changes throughout the years, with most occurring after swimmers found more effective ways of swimming the stroke, giving them a large advantage against their competitors. In the 1930s the revolution that recovering the arms above the water sped up the recovery process, forced a rule change that began the creation of butterfly and prevented the arms recovering out of the water in breaststroke. Similarly, when Masaru Furukawa of Japan completed most of his gold medal winning breaststroke 200 m race at the 1956 Olympics underwater, rule changes were made to ensure that the head must break the surface of the water during each stroke cycle and that the swimmer only performs one stroke underwater off a start and turn. This defined what we now know today as the breaststroke underwater phase.

In 2005, a single dolphin kick was permitted by FINA during the BUP in competition once the hands had started to separate. In 2014, FINA further amended this rule to permit a single dolphin kick at any point prior to the first breaststroke kick (Figure 1.1).

Breaststrokers have been found to spend more time underwater after their start and turn in comparison to the other competitive strokes. Male breaststrokers competing in the 2016 European championships spent an average of 4.47 s underwater after their dive entry, travelling on average 9.67 m underwater, compared to 2.95 s for male freestyle swimmers travelling 8.17 m (Morais *et al.*, 2018).

From analysis of races at the 2000 Sydney Olympics, Cossor and Mason (2001) found that male swimmers in the 100 m breaststroke had a significant correlation (r=

-.73) between the underwater velocity and time to 15 m. In addition, in the 200 m breaststroke, female swimmers had a significant correlation (r= .65) between underwater distance and time to 15 m and between underwater time and time to 15 m (r = -.78) highlighting the added importance that the underwater phase has in breaststroke. To obtain the data, Cossor and Mason (2001) divided the start into phases and the head of the swimmer was identified at key distances from gun time to when it broke the surface to begin free-swimming. Times at set distances were collected, and velocity of the swimmer based on tracking the head of the swimmer.

Swimming underwater does have an advantage over swimming on the surface, due to a reduction in resistance from surface waves (Barbosa *et al*., 2013). Specifically, within breaststroke, performing a full arm stroke and leg kick underwater can be beneficial, but to maintain a high underwater speed, each element of the BUP must be carefully coordinated and practised to maximise its contribution to 15 m (start time) and overall race performance (Seifert *et al.,* 2007). Seifert *et al.* (2007) state that to positively influence start time and future velocity, breaststroke swimmers must have the ability to correctly organise the start phases to gain the best outcome. They must also complete an effective arm to leg coordination pattern to increase forward displacement during propulsion, glide and recovery phases enabling for a longer underwater phase with minimal velocity loss and less instantaneous velocity fluctuations.

As the breaststroke underwater phase also consists of two different gliding positions, the ability to perform a low resistance streamline position in both 1st and 2nd gliding sub phases is key to minimising the loss of horizontal velocity (Breed and Young, 2003). Vilas-Boas *et al*., (2010) confirmed results that during the 1st glide the overall drag force is lower than during the 2nd glide. They determined that this could be due to reduced drag coefficient and reduced cross-sectional area shown to the water with the shoulders in the flexed position extended above the swimmer's head along the longitudinal axis of the body. Their practical advice based on these results was for coaches and swimmers to not only to focus on the propulsive elements but also the resistive elements of the BUP to improve performance. They highlighted the need to emphasise time spent in the 1st glide and reduced the time spent in the 2nd glide. They also stressed the importance to focus on the need for body position control throughout both glides, especially during the more resistive 2nd glide. If a swimmer can minimise the loss of horizontal velocity within the gliding sub phases, they will maintain a higher horizontal velocity through the resistive phases (Breed and McElroy, 2000).

In addition to the resistive glide phases, the BUP includes the recovery of the arms and legs. This consists of the swimmer bringing their arms from the 2nd glide position, next to their hips, through to under their body, to return to an extended streamline position, ready for the completion of the first stroke. As the Arm recovery is occurring, the swimmers must also decide when to recover the legs from a streamline position into a breaststroke kick position, ready for the propulsive kick phase of the BUP. This is a highly resistive phase and it increases on an already high drag force (Seifert *et al*., 2007). Seifert *et al.* (2007) found that both international and national level swimmers have a negative superposition coordination, meaning they overlap the two resistive phases of the Arm + leg recovery to maintain a high mean velocity throughout the BUP.

Ruschel *et al*. (2007) state that although the swimmer may have an advantage swimming underwater it is not beneficial for a swimmer to solely travel a long distance underwater or spend a large amount of time underwater. Instead, they must combine both variables by minimising the loss of horizontal velocity and maximising the propulsion during the underwater phase to perform a longer distance in a shorter time. Veiga, Roig & Gómez-Ruano (2016) found that when focusing specifically on breaststroke at the 2013 World Championships, faster swimmers did not necessarily spend a longer duration underwater than slower swimmers in the 100 m breaststroke however faster swimmers did have the ability to increase or maintain their distance travelled in the underwater phases on the last turn of the 200 m in comparison to slower swimmers.

2.4.1 Components of the Breaststroke Underwater Phase

The BUP includes six phases (Figure 1.1 and 2.4); a) 1st glide, b) dolphin kick, c) Pull-down, d) 2nd glide, e) Arm + leg recovery and f) kick. Three propulsive phases a) b) dolphin kick, c) Pull-down and f) kick, and three predominantly resistive phases, a) 1st glide, d) 2nd glide and e) Arm + leg recovery (Figure 1.1 and 2.4) (McCabe *et al*., 2022).

The 1st glide in breaststroke involves the swimmer gliding in a prone streamline position with their shoulders flexed, arms overhead, hands overlapping and feet together and plantar flexed (Naemi *et al*., 2010). During the glide phase the swimmer has a negative acceleration, and largely only drag forces are acting on the body, with no propulsion. The 1st glide phase commences at toe immersion from a start and feet leaving the wall on a turn and finishes with the separation of the hands for the Pull-down or the initiation of the dolphin kick. The single dolphin kick may be performed proceeding the 1st glide or it may be performed later. The dolphin kick consists of two phases; the upbeat (where knee flexion begins, and the feet move in an upward direction towards the surface of the water) and down beat (where knee extension begins and the feet move in a downward direction towards the bottom of the swimming pool) (Alves *et al*., 2006). The Pull-down phase is a propulsive phase and is the only occasion within a breaststroke race where a swimmer is permitted to bring their hands all the way back to their hips, if they choose to (Figure 1.1 and 2.4).

In the 2nd glide, which proceeds the Pull-down, the swimmer places their arms extended at the side of the trunk (Figure 1.1) and remains in a sufficient streamline position throughout. The Arm recovery phase is the forward movement of the arms that occurs after the propulsive element of the arm Pull-down and second glide. The Leg recovery phase is the lift of the heels to the buttocks in preparation for the kick (Figure 1.1 and 2.4). The Arm and leg recovery often occur at the same time, which if not coordinated correctly can lead to an increase in an already high drag. Often leg propulsion (kick) begins before the end of the Arm recovery with arms in streamlined position. The BUP is finished with a propulsive kick which often finished just before the swimmer breaks the surface of the water and transitions into their free-swimming (Seifert *et al*., 2007).

When looking in more depth, McCabe *et al.* (2022) identified that elite breaststrokers perform one of three pull-out techniques. The fly-kick first technique (fly-kick is initiated and completed prior to Pull-down), the combined technique (Pull-down is initiated before the fly-kick is complete, consequently an overlap of phases is observed) and the Pull-down first technique (Pull-down is completed prior to fly-kick) when competing in World and Olympic long course breaststroke events from 2015 to 2019. These three techniques differ slightly with respect to Seifert *et al.* (2021) who when focusing on short course time trials of 14 swimmers, identified three slightly different coordination profiles: "Continuity"; "Glide" and "Superposition". They defined the "Continuity" profile as the synchronisation of the arm Pull-down beginning as the fly-kick ends, which is similar to the fly-kick first technique as described by McCabe *et al.* (2022). The "Glide" profile was defined as the initiation of the arm Pull-down following a glide phase post completion of the fly-kick. This coordination profile was also incorporated within the fly-kick first technique by McCabe *et al.* (2022) due to the lack of underwater video footage and thus inability to identify a distinct glide portion following the fly-kick completion. The combined technique by McCabe *et al. (*2022) and Seifert *et al.* (2021) The "Superposition" profile is similar in that both identify an overlap of the arm Pull-down and completion of the fly-kick. In addition, McCabe *et al.* (2022) uniquely observed and identified the Pull-down first technique which was not evident within the Seifert *et al.* (2021) study.

McCabe *et al.* (2022) found that across all race distances (150 race entries across the 50, 100 and 200 m events), the most common underwater pull-out technique following a start and turn that was utilised by elite competitive breaststroke swimmers (male and female) was the combined technique (total observations = 71), followed by the fly-kick first technique (total observations = 65) and the Pull-down first technique (total observations = 14). Elite swimmers in this study were defined as those who competed in the final of an Olympics or World Championships. However, based on a year-by-year breakdown they found the fly-kick first technique was becoming more popular (McCabe *et al.*, 2022). When analysed as a whole (from 2015 to 2019) McCabe *et al*. (2022) results differ from Seifert *et al.* (2021) who found that based on their sample, the continuity profile (the fly-kick first technique) was more popular followed by the superposition profile (the combined technique). However, when specific years were isolated Seifert *et al.* results were in agreement with McCabe *et al.* (2022) results from 2019 specifically. Additionally, it was found by McCabe *et al.* (2022) that differences existed between the technique chosen for starts and turns by some elite swimmers. It is possible that skill level, sex and the length of the pool (short vs. long course), may all be contributing factors that influence the style of underwater technique utilised which requires investigation.

2.4.2 Measuring kinematic variables in swimming

Video analysis is commonly used for quantitative and qualitative analyses within aquatic environments such as swimming. Two-dimensional video protocols are regularly used to collect kinematic information to analyse start, turn characteristics and stroke mechanics. In previous research both static cameras (above and below water level) (Vantorre *et al*., 2011), moving cameras attached to a trolley (Seifert *et al*., 2010) or a combination of the two (Oxford *et al*., 2016) have been used.

Within swimming, the evaluation of mean speed and intra-cyclic (instantaneous) swimming velocity has been highlighted as a useful tool to assess overall swimming performance (Figueiredo *et al*., 2011). There are several methods to assess speed within swimming including digitising one or more points on the body to obtain 2D/3D coordinates to calculate 3D Centre of Mass (de Jesus *et al.,* 2012; Veiga, Cala, Frutos and Navarro, 2014) and devices such as velocity meters (speed reel) that measure the speed of a swimmer directly (Gourgoulis *et al*., 2018).

A large body of swimming research is completed using two-dimensional analysis (Seifert, Vantorre and Chollet, 2006; de Jesus *et al.,* 2012; Veiga, Cala, Frutos and Navarro, 2014). It is a less time-consuming method for data collection than 3D video analysis, there is a greater accessibility to equipment due to low equipment costs and quick feedback is achievable with simpler data analysis. 2D video analysis is regularly used by coaches for qualitative analysis (Callaway, 2015), however there are several limiting factors with 2D video analysis: often bilateral symmetry is falsely assumed due to acceptance that the movement being analysed is confined to a single, pre-defined plane. This presents large perspective errors when measurements are taken from outside this plane (Payton and Burden, 2017). This is a hugely limiting factor for swimming strokes, especially breaststroke and butterfly that are not a planar activity and must be viewed in a three-dimension to truly represent the motion of the whole body (Psycharakis *et al*., 2005). Additionally, three-dimensional rotation cannot be calculated from a single plane 2D video analysis and could contribute to the appearance of 2D sagittal kinematics (Schurr, Marshall, Resch and Saliba, 2017).

3D video analysis improves the limitations of 2D analysis as it eliminates perspective errors present within 2D analysis and the incorrect representation of joint angles due to the contribution of rotation and the assumption of bilateral symmetry as it allows the true spatial movements of the performer to be quantified (Payton and Bartlett, 2008). When completing 3D analysis within swimming, cameras are often submerged in waterproof housing, with additional above water cameras poolside and placed surrounding a specific area and focused on the calibrated volume similar to that completed in out of water data collections (Silvatti *et al*., 2013). Using either static or dynamic calibration systems with objects consisting of control points with known distances, a calibrated volume can be created with a high level of accuracy (Silvatti *et al*., 2013).

Although 3D analysis methods and equipment have been found to be accurate when analysing swimming (Silvatti *et al*., 2013) there are several drawbacks that are related to the method. It is a more expensive method of analysis with larger equipment requirements (Payton and Bartlett, 2008). As multiple cameras are essential for 3D analysis, there is a much greater amount of digitising required to track the displacement of markers placed at specific anatomical locations (Mooney *et al*., 2015), increasing manual post processing time. When manually digitising Magalhaes et al., (2013) estimated based on data from Psycharakis and Sanders (2008) that it takes 27 hours to digitise 1,620 frames (19 anatomical landmarks for 6 cameras over four stroke cycles of one swimmer). Additionally, difficulty arises processing images due to the swimmer transitioning between the water-air interface (the parallax effect) (Kwon, 1999), turbulence/ bubble formation (Mooney *et al*., 2015a), water clarity and light reflexion.

Although data processing is time consuming and random errors can be caused through manual digitisation (Wilson *et al*., 1999; Mooney *et al*., 2015a) within swimming it is a more appropriate choice than the laboratory condition 'gold standard' of three-dimensional optoelectronic analyses (Payton, 2008). Contrast between the reflective markers and the background and turbulent water can obscure the markers and introduce additional error in automatic procedures (Payton, 2008). An increase in drag and reduction in performance has also been found as a result of increases in drag of the reflective markers (Washino *et al*., 2019) with Kjendlie and Olstad (2012) finding an increase of 7% to 10% in passive drag (24 markers, 19mm diameter).

More recently, a further development in this field is the use of markerless technology (Ascenso *et al*., 2020). This removes the requirement for markers to be applied to swimmers or the lengthy process of digitisation. Markerless technology requires the automatic extraction of the contour (the silhouette) of the swimmer and the locations of the swimmer's joints (referred to as 2D joints) in camera coordinates. This technology is at the forefront of swimming research however, it is yet to be accomplished without error (Ascenso *et al*., 2020).

On land, radar guns, GPS units, IMUs and 2D/3D video analysis are frequently used to measure speed (Talukdar, Harrison and McGuigan, 2021; Alphin *et al*., 2020; Zeng *et al*., 2022). However, an aquatic environment comes with restrictions such as waterproofing equipment and specifically, with video analysis, bubble formation and light refraction are further limitations (Feitosa *et al*., 2013). Additionally, adding equipment to swimmers such as IMUs can increase drag unlike video based systems (Hamidi Rad *et al*., 2021). Due to all of these restrictions highlighted above, velocity meters are a quick and affordable way of assessing the instantaneous speed of a swimmer evading the limitations of aquatic environments (Feitosa *et al*., 2013). Velocity meters are commercially available systems (Swim speedometer, Swimsportec®, Hildesheim, Germany) that have been validated against the intra cyclic variation of the 2D greater trochanter velocity by numerous researchers (Feitosa *et al*., 2013; Morouco *et al* 2006). Feitosa *et al*. (2013) found that, compared to a single sagittal camera used to obtain 2D hip centre velocity, a velocity meter accomplished all their validation criteria. They identified no significant differences for pair-wise comparisons between the speedo-meter system and the videometric system (> .05), very high associations for all variables were identified via the linear regression models (all, $R^2 > .9$; $p < .001$) and more than 80 % of the Bland-Altman plots were within the 1.96 standard-deviation criterion. This enabled Feitosa *et al*. (2013) to conclude the velocity meter to be an appropriate apparatus to assess human horizontal intra-cyclic velocity specifically when completing breaststroke and butterfly strokes. However, to gain more information on the swimmers CoM velocity and further calculate drag or propulsion, a limitation to both the 2D hip centre velocity or a velocity meters are that they do not represent a swimmer's mass centre velocity as they collect the speed of a fixed point (Figueiredo *et al*., 2009)

In a comparison of three of the above approaches, the CoM obtained from 3D video analysis will provide the most accurate measure of the speed of the whole swimmer and could be considered the gold standard criterion against which the other two methods should be compared. However, as the hip (2D video) and Speed Reel both measure the speed of a fixed point on the body, they will not produce the same speed-time profile as the CoM (not a fixed point in the body). Therefore, any differences between the three data sets should not be considered as errors (true value – measured value) as each approach could be providing an equally accurate measure of what it is intended to measure.

This is supported by research completed by Gourgoulis *et al. (*2018) who found that during the free-swimming phase of breaststroke, the hip centre intra-cyclic speed overestimates maximal values and underestimates minimal values in comparison to centre of mass speed. The over and underestimations have been found to be due to the intersegmental actions during breaststroke swimming. The underestimation during the arm and leg recovery phase occurs due to the forward displacement of the upper and lower limbs throughout this phase causing the CoM to decelerate less than the hip centre and consequently, the hip records much lower speeds (Maglischo, Maglischo and Santos, 1987). The overestimation at peak kick speed can be attributed to the hip accelerating to a greater extent than the CoM due to the backward movement of the legs during the kick affecting CoM speed (Gourgoulis *et al.* 2018).

2.4.3 Speed-fluctuation during the BUP

The BUP involves a considerable amount of speed fluctuation (Figure 2.4), typically the swimmer experiences three speed peaks created during the propulsive phases in addition to two velocity minima associated with the glide and recovery phases. The challenge to the swimmer is to adapt timings and method to increase propulsion when the instantaneous velocity decreases below the mean swimming velocity, and to glide when the instantaneous velocity is above the mean swimming velocity (Seifert *et al*., 2007).

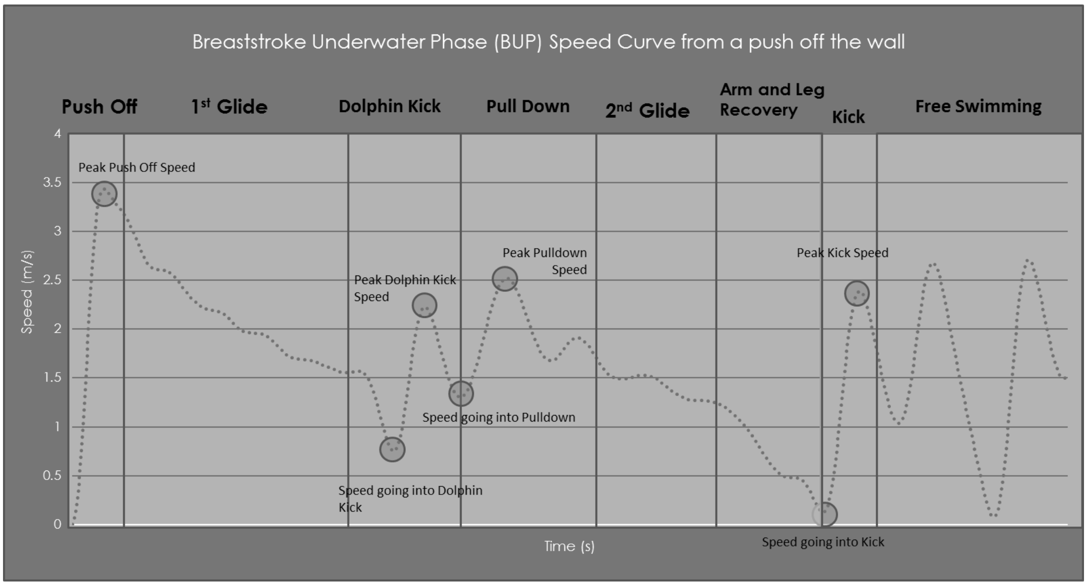


Figure 2.4: Speed Curve of the BUP (Example of British Swimming speed reel data to highlight the velocity fluctuations within the breaststroke underwater phase).

The breaststroke underwater phase differs considerably from that used in the other three strokes as it consists of two different glides (Figure 1a, 1d and 2.4). The aim of a glide is to maintain a high underwater speed whilst not completing any propulsive actions (Naemi *et al*., 2010). During the 2nd glide, completed post Pull-down, the swimmer's body has a higher drag coefficient (0.664) than during the 1st glide (0.458); differences in body position account for the differences in these hydrodynamic drag coefficients (Vilas-Boas *et al*., 2010). Consequently, based on their results Vilas-Boas *et al.* (2010) emphasised to coaches the need to focus on the streamline position, specifically in the first glide due to its lower drag coefficient. Secondly, body position control and minimisation of time spent in the 2nd glide should also be considered (Vilas-Boas *et al*., 2010). This statement should be reviewed further, and additional research is required to provide evidence to support this statement, particularly regarding the minimisation of time spent in the 2nd glide.

D'Acquisto *et al.* (1988) completed research on a breaststroke stroke cycle within free-swimming, not the underwater phase, comparing the stroke cycle of 'superior' to 'good' breaststrokers, grouped based on their best 100-yard time. It was found that superior breaststrokers covered a greater distance in a shorter time period during arm + leg recovery than good breaststrokers. Superior males and females also achieved a 33% and 20% (respectively) greater glide distance during the free-swimming phase than good breaststrokers. This suggests that in addition to the influence of a potentially higher velocity, superior breaststrokers may also maintain a more streamline position during the glide and in the later stages of the Arm recovery which could directly influence their glide ability within the BUP.

The Arm + leg recovery phase (Figure 1e) has been stated to have an increased level of drag in comparison to the 1st and 2nd glide (Seifert *et al*., 2007). This is due to the body being less streamlined during these recovery phases, increasing in the drag coefficient and the frontal area presented to the flow of the water (Kent and Atha, 1970). This increase in cross-sectional area directly affects drag by increasing the form drag created because of the pressure difference between the distal and proximal segments of the body (Naemi *et al*., 2010). National and international swimmers have both been observed to create an increased drag, in comparison to the glide phases, within the recovery phases due to a negative superposition of the end of Arm recovery and the beginning of leg propulsion, consequently increasing cross-sectional area (Seifert *et al*., 2007). However, the overlap has been suggested to be an effective strategy to anticipate the beginning of leg propulsion (Seifert *et al*., 2007). Chollet *et al.* (2004) and Seifert *et al.* (2007) found that top swimmers performed this overlap of phases to increase their mean velocity within the free-swimming and the BUP respectively, as waiting for the end of Arm recovery in a streamline position did not maintain a high velocity.

Some breaststroke swimmers perform a dolphin kick as their initial propulsive phase within the BUP (Figure 1b and 2.6) (Seifert *et al*., 2021). Although research has been completed into multiple dolphin kicks such as the technique performed during the underwater phases of the freestyle and butterfly strokes (Willems *et al*., 2014), due to continual rule changes there is minimal research on the dolphin kick within BUP under the new constraints. Within the BUP, only a single dolphin kick is allowed to be performed and although the sequencing of a downbeat and upbeat may be similar, the cyclic patterning that is performed in other strokes is not. Consequently, the dolphin kick within the BUP needs further kinematical analysis to identify the key performance variables.

Research that has been conducted on the BUP fly kick, however, has investigated the ideal placement of the dolphin kick within the BUP. McCabe, Mason and Fowlie (2012) found that where the dolphin kick is performed with the BUP (early or late) does not appear to influence the performance time of the underwater phase following a start or turn. However, it does affect breakout distance, with swimmers who performed an early placement fly kick breaking out significantly further than those who delayed the fly kick and performed it within the arm Pull-down. Although fly kick placement was not found to significantly influence underwater performance, McCabe, Mason and Fowlie (2012) stated that the placement of the kick must still be considered in regard to energy cost, physiological understanding throughout a race or specifically in sprint events where swimmers may want to commence free-swimming earlier. However, when solely looking into the overlap/superposition, Hayashi, Homma and Luo (2015) used a computational simulation model called SWUM to identify that there is a more ideal placement of the dolphin kick in comparison to other placements, with the dolphin kick being completed approximately 0.4 seconds faster than Pull-down initiation. They identified the reasoning as the ability to maintain a streamline position for longer before the initiation of the pull will reduce water resistance and drag prior to the propulsive phase of the fly kick and Pull-down being completed.

The Pull-down within the BUP (Figure 1c and 2.4) is a propulsive phase and if performed well and continually developed, it can maximise the amount of time a swimmer can travel above their free-swimming velocity and will enable the swimmer to travel a further distance at a higher velocity underwater than they have previously achieved (Alcock, 2015). Alcock (2015) found that when determining the effect of timing on the breaststroke Pull-down, if a lower skill level swimmer initiates their Pull-down earlier by spending less time within the 1st glide phase and reduces their 2nd glide time, they can improve their time to 13 m by 0.03 s. If this were completed within a 200 m breaststroke event, a swimmer could gain a 0.12 s advantage over their opponents (Alcock, 2015).

Although no research has been completed on further kinematics of the Pull-down, research has been conducted into the hand speed and trajectory of hands in a butterfly arm cycle as this could be seen as comparable to a breaststroke Pull-down with the arms starting above the head and ending by the hips. Barbosa *et al*. (2008) found that the horizontal velocity of the hands within the insweep and upsweep of a butterfly stroke was also found to have a significant association to horizontal swimming velocity, therefore, identifying hand speed as a key metric within a Pull-down to increase horizontal velocity and overall underwater performance.

The breaststroke kick is the last propulsive sub-phase within the BUP (Figure 1f and 2.4). Seifert and Chollet (2005) proposed breaking the breaststroke kick down into 5 parts: leg propulsion, leg in sweep, leg glide, first part of the recovery until a thigh/leg angle of 90° and second part of the recovery. However, when completing further biomechanical analyses Kippenhan (2001) focused on 4 phases by analysing the recovery phase as one, not two parts, Olstad *et al.* (2014) followed the Seifert and Chollet (2005) model however removed the leg glide phase and Matheson *et al*. (2011) solely focusing on the propulsive element of the kick.

Although there is limited research into the breaststroke kick during the underwater phase, research has been completed during free-swimming and has found that a large plantar flexion and inversion angle, and a greater angular velocity during the early propulsive phase contributes to a greater hip speed overall (Matheson *et al*., 2011). Kippenhan (2001) also identified that higher level swimmers had wider ankle positions than lower standard swimmers however, the entire hip and ankle joint range of movement available in the breaststroke was not used by the most skilled swimmers. Jagomägi and Jürimäe (2005) stated in agreement that the more flexible the ankles and knees are, the easier it is to keep the kick narrow and kick back rather than out. Additionally, Strzała *et al*. (2012) found that foot slip in the water was significantly negatively correlated to horizontal body displacement. Considerable further work is required to identify the optimum way to perform the propulsive and recovery actions of the arms and legs during the BUP.

Olstad *et al.* (2014) found knee angle at the beginning of the knee extension phase went from 44.8° at 60% effort to 42.3° at 100% effort with the duration the participants spent in each kick phase being between 0.46-0.5 s, 0.51 – 0.87 s and 0.41 – 0.52 s. Olstad *et al*. (2014) concluded that there was an increase in kick cycle velocity when effort levels were increased and this was largely due to the change in minimum knee angle at the beginning of the knee extension, with swimmers' heels being closer to the buttocks at the 100% effort enabling then to create a further distance for their feet to travel and provide force on the water. In addition, elite swimmers were found to minimise the time spent in the knee extension phase and knee flexion phase indicating a more explosive recovery and maintaining speed and increasing momentum when swimming at 100% effort. These knee angle results are similar to Olstad *et al*. (2017) who found marginally larger angles for the smallest knee angle of 48°. In addition to knee angles, Olstad *et al*. (2017) also found there to be a consistent foot slip ranging from 300-320 mm which was similar across the subjects, irrelevant of knee angle or technique.

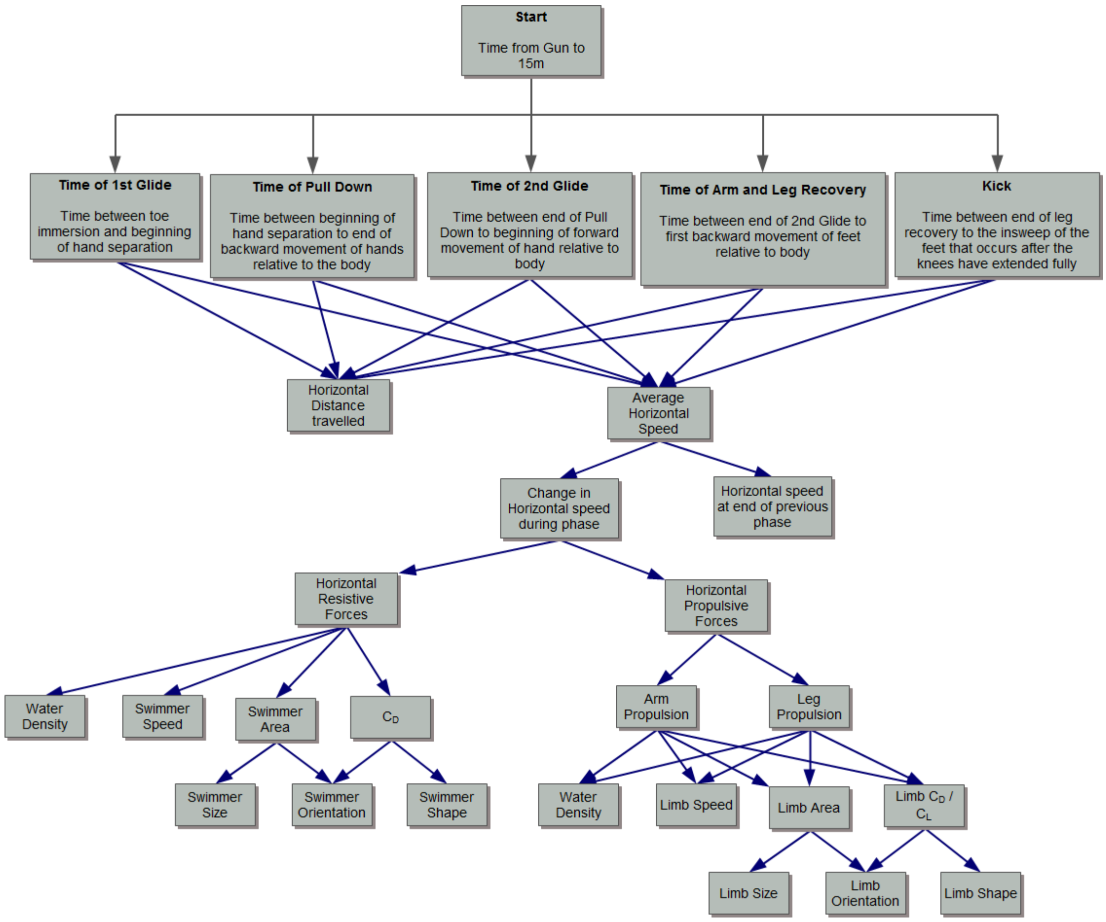


Figure 2.5: Deterministic Model of a BUP (without dolphin kick) (Created as original work by the author of the thesis).

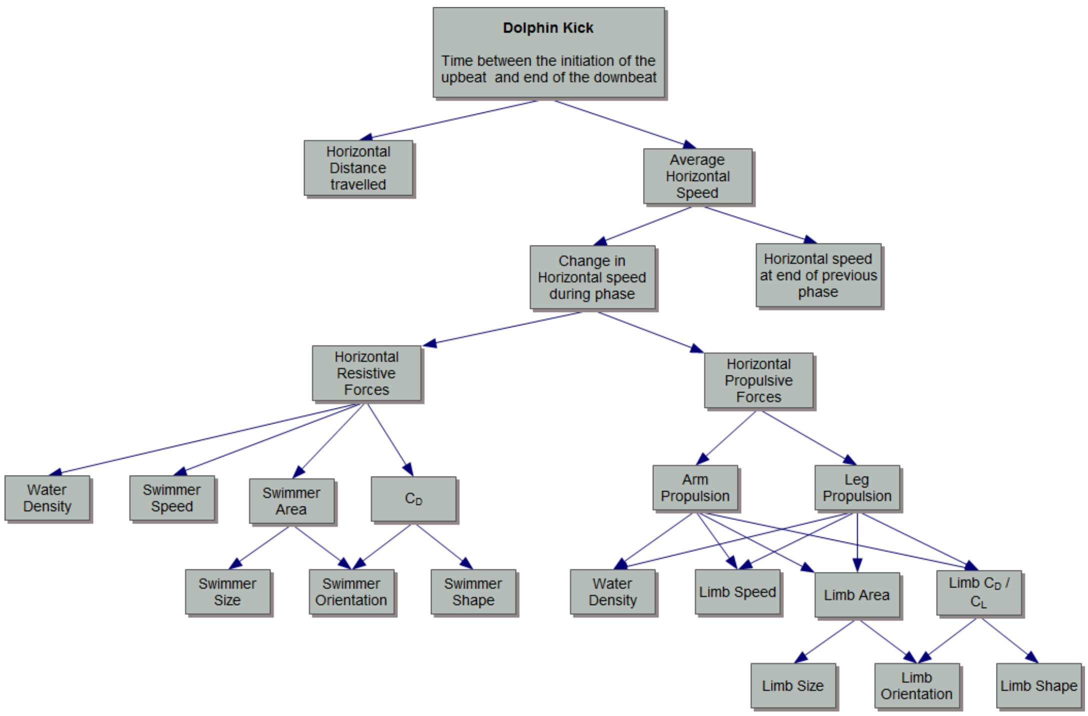


Figure 2.6: Deterministic Model of a dolphin kick (Created as original work by the author of the thesis).

2.5 Drag

Drag force (F_D) is an external force acting on a swimmer in the opposite direction to their displacement (Barbosa *et al.*, 2015). With the addition of intensity of these forces relating to the speed of the swimmer, total drag can be calculated (Cortesi and Gatta 2015).

Passive drag force can be calculated using the below formula:

$$F_D = 1/2\, \rho \cdot v^2 \cdot C_D \cdot A$$

F_D = drag force, ρ = density of water, v = velocity, A is the projected frontal surface area and C_D is the coefficient of drag. There are two forms of drag that are measured in swimming: passive and active. Passive drag is the drag force acting on a swimmer when they are gliding in a passive stable position and is not moving any part of their body (Cortesi and Gatta, 2015). This is largely affected by the shape and size of the swimmer's body and the velocity they are travelling. Active drag is defined as all drag forces acting on a swimmer during free-swimming or any aspect of limb movement (Kjendlie and Stallman, 2008).

For both forms of drag (F_D) there are three main components that act on the swimmer: Friction/skin drag (F_F), form/pressure drag (F_P), and wave drag (F_W) (Vennell, Pease and Wilson, 2006). Friction/skin drag results from the resistive force caused between the water and the swimmer's surface. This is determined by the characteristics of the surface i.e. the height and shape of the irregularities on the surface of the object, within a swimming context this is the swimmer's skin roughness (Naemi, Easson and Sanders, 2010).

$$F_D = F_F + F_P + F_W$$

Form/pressure drag is the result of the pressure differences between the leading and trailing edges of the body times the area to which the pressure is applied (Naemi, Easson and Sanders, 2010) and is associated with the wake of the swimmer (Vennell, Pease and Wilson, 2006). When a smooth flow of water is distorted over the swimmer, due to the size and shape of a swimmer and their travelling velocity, a variation in pressure between the front and tail-end of a swimmer is created. Consequently, pressure drag equates to the pressure difference and the cross-sectional area of a swimmer (Toussaint & Truijens, 2005). Huijing *et al. (*1988) and Benjanuvatra, Blanksby, and Elliott (2001) concluded that body size and cross-sectional area was a large determinant of drag. However, more recently, Naemi *et al. (*2012) stated that although drag is influenced by anthropometrics, when gliding, swimmer's shape characteristics have a larger influence on glide efficacy with postural angles having a greater effect on that cross-sectional area. Their findings suggest that a swimmer with a larger cross-sectional area could create less drag than a swimmer with a smaller cross-sectional area, if compensated for with the appropriate shape.

Wave drag is mainly caused by the energy required to form waves when swimming on or near the surface of the water. Vennell, Pease and Wilson (2006) found that drag force measurements can increase up to 2.4 times the drag when swimming at a depth of 0.4 m or less in comparison to being fully immersed. Specifically, wave drag of less than 5 % of the total drag was found when travelling equal or deeper than 0.7 m at 2.0 $m \cdot s^{-1}$ and equal or deeper than 0.5 m at 1 $m \cdot s^{-1}$ (Vennell, Pease and Wilson, 2006). These results therefore recommend that a swimmer should glide at a depth of 0.5 m or greater when travelling between 1 and 2 $m \cdot s^{-1}$.

2.5.1 Measuring passive drag

Passive drag is the drag force acting on a swimmer when they are not utilising their limbs to generate propulsion and are gliding in a passive stable position (Cortesi and Gatta, 2015). Gliding occurs during the underwater phase of a start and turn for all strokes, however, it is more prevalent in breaststroke due to the two glide phases. Additionally, the importance of the glide phase is further increased, especially with 200 m breaststroke swimmers, as it is a part of the stroke cycle within free-swimming (Naemi & Sanders, 2008). Therefore, the aim of the swimmer in these glide phases, is to minimise their passive drag and prevent a large deceleration prior to initiating any propulsive movements (Guimaraes and Hay, 1985). This reduction in passive drag can contribute to an overall quicker race time (Scurati *et al*., 2019).

Passive drag can be measured in a streamline position or 2nd glide position using an automated towing machine mounted on pool side, connected to a force-transducer or mounted on force blocks (Mollendorf *et al*., 2004; Webb *et al*., 2011) or within a swimming flume (Chatard and Wilson, 2003, 2008; Narita, Nakashima and Takagi, 2017). Passive drag is measured in the streamline position by holding a handle that is attached to the towing cable, above the swimmer's head, or in the 2nd glide position of the BUP, the swimmer is attached to the towing line with a harness either placed around their waist or under their armpits (Mollendorf *et al*., 2004; Webb *et al*., 2022).

Researchers regularly collect data covering a range of velocities to create a force/velocity curve for that individual swimmer (Tor, Pease and Ball, 2015). This enables multiple passive drag measurements to be applied throughout a swimmer's skills and free-swimming components of their race. These velocity ranges are often selected between 1.0 m·s-1 and 2.5 $m \cdot s^{-1}$ as these velocities include all common velocities reached by swimmers within a race (Benjanuvatra, Blanksby and Elliott, 2001; Gatta, Cortesi and Zamparo, 2016; Tor, Pease and Ball, 2015). Tor, Pease and Ball (2015) found that the highest mean velocity performed by elite male swimmers was after the immersion from the start at 2.38 $m \cdot s^{-1}$, therefore there is minimal requirement to complete passive drag testing above this velocity. Although the number of velocities used in studies differ (Benjanuvatra, Blanksby and Elliott, 2001; Cortesi and Gatta, 2015), Cortesi and Gatta (2015) highlight the importance of using a large variety of velocities that the tested swimmer could complete as they showed that when a swimmer completes a passive streamline position with their head in a neutral position the passive drag can range from 77.1 N at 1.5 $m \cdot s^{-1}$ to 120.6 N at 1.9 $m \cdot s^{-1}$.

When using a towing system, the resistance on the body of the passive swimmer is collected as they are towed through the water at the known speed and the force is collected via the force applied through the inelastic towing line to the force transducer or force block. As depth is known to affect the drag of a swimmer (Vennell, Pease and Wilson, 2006), with Tor, Pease and Ball (2015) finding a 19% to 23% passive drag change dependent on depth and regardless of speed, some researchers such as Lyttle *et al. (*1998) accounted for this by fixing an adjustable pully system to the pool wall for the towing cable to be mounted at key depths for the swimmers to be towed at.

The flume method differs to the above towing method as the swimmer remains held in a fixed location whilst the water is propelled toward them at a specific speed. This technique is regularly completed with swimmers (Chatard and Wilson, 2003, 2008; Narita, Nakashima and Takagi, 2017) and using a mannequin (Bixler, Pease and Fairhurst, 2007; Vennell, Pease and Wilson, 2006).

When reviewing the techniques and considerations for monitoring swimmers' passive drag, Scurati *et al. (*2019) found that the towing method was most commonly used for measuring passive drag due to an easier assessment procedure. Subsequently, the familiarization a swimmer has within a pool can also justify this method. Additionally, the laminar flow that is present in towing is a much similar condition to that of actual gliding in comparison to the potential turbulent flow that can occur during flume methods with water backflow increasing at higher velocities (Bixler & Riewald, 2002). They also found that there was a consistency of results across all methods included in their review including using a towing machine in a pool, a towing machine in a flume and a carriage in tow tank with 93% of their passive drag values being between 0.4 and 1 N.

2.6 Relationship between drag and performance

Specifically, when looking into the effects of drag on start performance, research heavily focuses on the gliding component of a start (Benjanuvatra, Blanksby and Elliott, 2001; Gatta, Cortesi and Zamparo, 2016; Tor, Pease and Ball, 2015). Within breaststroke this is highly important as the breaststroke underwater phase consists of two different gliding position where, during these glide phases, the swimmer has a negative acceleration, and largely only drag forces are acting on the body with no propulsion.

During the 2nd BUP glide, the swimmer's body has a higher drag coefficient (0.664) than during the 1st glide (0.458) and consequently an overall higher drag score (Vilas-Boas *et al*., 2010). This will have a direct impact on the horizontal velocity that a swimmer can maintain (Vilas-Boas *et al*., 2010). The ability to perform a low resistance streamline position in both 1st and 2nd gliding sub phases is key to minimising the loss of horizontal velocity (Breed and Young, 2003). If a swimmer can minimise the loss of horizontal velocity within the gliding sub phases, they will maintain a higher horizontal velocity through the resistive phases (Breed and McElroy, 2000). Vilas-Boas *et al. (*2010) practical advice, based on these results was for coaches and swimmers to not to focus solely on the propulsive elements of the BUP to improve performance. They highlighted the need to emphasise the time spent in the 1st glide and reduced the time spent in the second glide and they also stressed the importance to focus on the need for body position control throughout both glides, especially during the more resistive 2nd glide.

Supporting the above statement, Cortesi and Gatta (2015) found that based on the placement of the head within both glides, a reduction of 4.0–5.2% in mean passive drag was found when the head was down or aligned with the swimmer's arms alongside the body (2nd glide), in comparison to the head-up position. In additional they found a much greater result of a decrease of 10.4–10.9% in passive drag when the head was down or aligned with the swimmer's arms above the swimmer's head (1st glide). However, Barbosa *et al. (*2011) noted that it is important to look at active drag, and not solely passive drag, because the variables pertaining to drag forces can change when the subject in the water is actively moving, in contrast to being towed through the water.

2.6.1 Computational Fluid Dynamics (CFD)

Computation Fluid Dynamics (CFD) is a type of fluid mechanics which takes the swimmer as an object via 3D scanning and recreates them in a computer-simulated environment. It is a numerical approach that enables the researcher to simulate fluid flow around an object to determine metrics such as passive drag (Scurati *et al.,* 2019). Due to the ability to replicate identical trials and make accurate changes the common use for CFD is to investigate the changes in passive drag based on the use of different equipment, the changes in head position, angle of attack and depth of the swimmer (Scurati *et al.,*2019). When comparing CFD to a mannequin and swimmer in a flume in a streamline position Bixler, Pease and Fairhurst (2007) found less than a 4% difference in drag between their CFD model and their mannequin test results. This highlighted the validity of the CFD technique when calculating the passive drag of a swimmer. However, when these results were then compared to a real swimmer in a flume, they found a difference of 18% which was deemed 'less than satisfying'. Bixler, Pease and Fairhurst (2007) concluded the difference in results was accounted for by the inability of the swimmer to hold a stationary streamline position throughout the trials, with an increase in angle of attack from zero being recorded with an increase in water velocity. Additionally, the requirement of the swimmer to hold a handle placed their hands in a different position to that in the CFD and mannequin tests, which contributed to the overall drag. A potential improvement to testing the validity of the CFD technique could have been improved by scanning the swimmer and recreating the exact body position in the flume using a mannequin. This approach would have removed the limitations above.

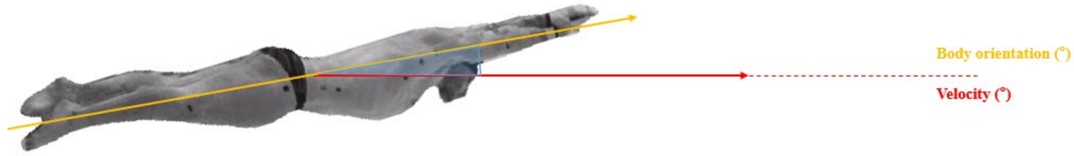
2.6.2 Angle of attack

The angle between the orientation of the body or a body segment to the direction of flow is referred to as the angle of attack of the swimmer or their angle of attack (Bilinauskaite *et al.*, 2013; Naemi, Easson and Sanders, 2010). Body orientation has been defined by researchers as a line drawn from the tip of the middle finger to the ankle bone or vertex to ankle bone (Bixler, Pease and Fairhurst, 2007; Marinho et al., 2009).

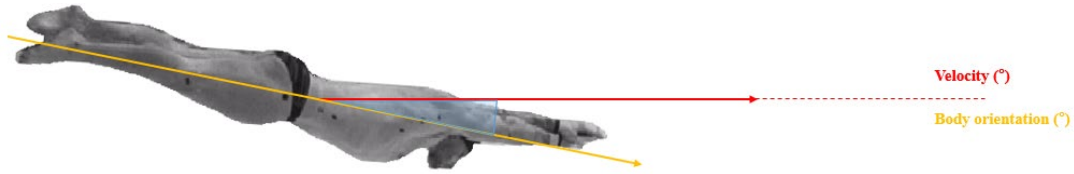
By using CFD, researchers have investigated how slight changes in the angle of attack of the swimmer contribute to hydrodynamics (Bilinauskaite *et al*., 2013). Based on previous research it is known that if the orientation of the swimmer's body is aligned to the direction of flow, their angle of attack equals zero and provides the minimum drag values in comparison to other angle of attacks (Bixler, Pease and Fairhurst, 2007). If the orientation of the swimmer's body is different to the direction their centre of mass is travelling and consequently changing the direction of flow, this results in an increased cross-sectional area that the swimmer is showing to the water and therefore increases the drag acting on the swimmer (Bixler, Pease and Fairhurst, 2007). Bixler, Pease and Fairhurst (2007) found that, when increasing the angles of attack to +3° and -4.5° from the horizontal orientation, there was an increase in drag of 2.3 and 2.4% respectively.

Positive angle of attack is identified by Hussain *et al. (*2011) as "nose-up" when describing pitch in flight, therefore when applied in a swimming context it is identified where the hands or head of the swimmer is higher in the water than the feet (Figure 2.7b). With negative pitch being identified as the swimmer's feet being higher in the water than the head/hands (dependent of what glide phase the swimmer is performing) (Figure 2.7c). Pease and Vennell (2010) found there to be a difference between a positive and negative angle of attack, specifically when being performed at different depths. If a swimmer displays a positive angle of attack close to the surface of the water the separation of the water flow occurs earlier and has a larger direct impact with the free water surface, consequently increasing wave drag and thereby total drag. However, if the swimmer is in a negative angle of attack at the same depth the water separation flows more on the underside of the swimmer reducing the surface interaction and consequently the wave drag is not as high.

2.7a



2.7b



2.7c

Figure 2.7: a) CoM velocity travelling in the same direction as the body is pointing = 0 angle of attack. b) CoM velocity travelling downwards based on the direction the body is pointing = +ve angle of attack. c) CoM velocity travelling upwards based on the direction the body is pointing = -ve angle of attack

A limitation to both Bixler, Pease and Fairhurst (2007) and Pease and Vennell (2010) are the minimum and maximum angle of attack values they tested, with neither study looking into angle of attacks greater than +/- 4°. This was highlighted as a limitation as in real swimming situations much larger angle of attack may be observed Pease and Vennell (2010). When researching in flumes or with CFD the flow of the water is always travelling in a horizontal direction therefore 0° of pitch is a perfect horizontal line. However, when using a real swimmer in a pool, the direction of flow of the water changes based on the direction the swimmer's centre of mass is travelling. As a result of these differences in water flow, researchers define angle of attack based on the horizontal line (Pease and Vennell, 2010) when utilising angle of attack in CFD and flume (mannequin) studies but define it as the angle between the orientation of the body and the direction their centre of mass is travelling (Naemi, Easson and Sanders, 2010) in experimental studies using swimmers in a pool.

More research into the application of CFD in to real swimming situations is required. Utilising 3D kinematic data and linking with CFD models could provide a method of further understanding the effect of drag on the BUP.

As evidenced above, this literature review has highlighted that limited research exists on the BUP, especially on the 3D investigation of the BUP and the use of elite swimmers within the research that has been published. Given the impact a breaststroke start and turn could have on overall race performance and the minimal research available, this thesis will add to the growing areas of research by being the first to provide a full kinematic analysis of the BUP involving a detailed analysis of its phases, which will contribute to the technical improvement of GB breaststrokers.

3 Chapter Three: Start and turn performance of GB breaststrokers in competition.

3.1 Introduction

Race analysis is the method of extracting key performance metrics from a video recording of a swimming race to learn more about the strategies used by swimmers and to explore where race winners have excelled in comparison to the rest of the field. This information is often reported back to the coach and athlete during the competition to improve their performance through the rounds, monitor improvements in race skills and stroke parameters or to indicate how the swimmer performed in relation to their competition model. Additionally, post-competition these data are used to highlight areas of improvement that need to be prioritised and developed in training (Veiga *et al*., 2012). Race analysis is now used by a large number of swimming national governing bodies (NGBs) at all major international competitions with British Swimming being one of these NGBs. Bespoke race analysis software "NEMO", developed by Sheffield Hallam University and the English Institute of Sport (EIS) for British Swimming, allows users to identify and 'tag' multiple events throughout a race, including individual arm strokes, when swimmers reach key distances such as 15 m, and the completion of underwater segments following the dive start and turn push-offs. From these data, variables relating to skills such as starts, turns, finishes and free-swimming, can be calculated.

The four components of a swimming race are broken down into: the start; turns; free swimming and finish. Various distances have been used when analysing these components to quantify performance of starts and turns. The vast majority of researchers and applied practitioners define start performance as the time from the starting signal to the head reaching 15 m, due to the lane rope markings at competition. In all strokes bar breaststroke, the swimmer's head must break the surface before it reaches 15 m, also making 15 m a suitable distance for assessing start performance in race analysis (Mason and Cossor, 2000). However, there is less consensus and standardisation when measuring turn time. Turn time has been defined as 7.5 m into the wall and 7.5 m out of the wall by Mason and Cossor (200), whilst others have used the time taken from 5 m into the wall until 10 m out of the wall (Mason *et al*., 2014; Kjendlie *et al*., 2006). More recent studies have defined turn time using 5 m in to 15 m out (Veiga & Roig, 2017; Morais, *et al*., 2018). The lack of consensus on the definition of turn time makes direct comparison between some race analysis-based studies difficult. Given that swimmers are permitted to travel up to 15 m underwater on their turns, using 7.5 m, or even 10 m to define the end of a turn may be inappropriate as many swimmers will still be performing the underwater phase of the turn at these distances (Veiga *et al*., 2012). The finish time is invariably defined as the time from the swimmer's head being 5 m from the pool wall, at the end of the race, to when the hands touch the wall. Free swimming is considered as all segments of the race not included in the start, turns and finish.

The practical benefit of defining start performance as the time to 15 m is the ease of identifying a swimmer at a known distance, thus enabling swimmers, coaches and sports science staff to compare skills to others and to identify weaknesses or to modify strategy on subsequent performances. A limitation to using 15 m when assessing turns is that a large proportion of that 15 m may involve free swimming (Veiga & Roig, 2015). Due to the individuality of each swimmer's start, turn and breakout distances (the distance travelled underwater following starts and turns) will influence the amount of free swimming that is included in the start or turn time to 15 m. Some swimmers utilise the whole 15 m to swim underwater, taking advantage of the reduction in wave drag that swimming below the surface affords (Lyttle *et al*., 1998); other swimmers opt to breakout earlier as they believe their free swimming on the surface to be faster than their underwater speed (Veiga *et al*., 2012).

Several researchers have highlighted the importance of start and turn performance on predicting the overall race performance for all swimming events (Mason and Cossor 2000; Olstad *et al.* 2020). Specifically, within Breaststroke, Mason and Cossor (2000), Olstad *et al.* (2020), Thompson, Halkand and MacLaren (2010) and McCabe *et al.* (2022) reported significant correlations between start time and race time in men's 100 m breaststroke. Mason and Cossor (2000), Thompson, Halkand and MacLaren (2010) and McCabe *et al.* (2022) also found strong correlations between start time and race time for 100 m women's breaststroke and 200 m men's and women's breaststroke with Sánchez *et al.* (2021) also finding strong correlation coefficients between r = .76–.91 in both 50 m and 100 m events across both sexes.

Turn times have also been found to have a strong correlation with race time in the men's 200 m breaststroke (Mason and Cossor 2000; Thompson, Halkand and MacLaren 2010 and McCabe *et al*., 2022), men's 100 m breaststroke, women's 100 m breaststroke and women's 200 m breaststroke (Thompson, Halkand and MacLaren 2010; McCabe *et al*., 2022) in both long course and short course swimming (Sánchez *et al*., 2021; Olstad *et al.,* 2020).

Based on coaches' and practitioners' observations within British Swimming there exists a perception that Great Britain (GB) swimmers are relatively poor on breaststroke starts and turns, compared to their free-swimming ability. As a result, a group of experts was brought together from academic institutes, sports organisations and commercial companies to form the Drag Reduction Working Group where starts and turns were identified as an area that required more focus and resource. This focus and resource created a small number of PhD projects focussing on differing areas of the skills, including this PhD focussing on the underwater phase of breaststroke. An initial aim of this PhD research was to provide evidence to support or refute this perception. A detailed analysis of GB breaststrokers' starts and turns in comparison to the world's best is thus warranted.

The aims of this chapter are to:

1. Determine the strength of association between breaststroke swimmers' start and turn times and overall race time in each breaststroke event, over multiple international competitions to highlight the importance of start and turns in a breaststroke race;
2. Compare personal best (PB) start and turn times of GB breaststroke swimmers to those of their international counterparts;
3. Establish the difference between GB and international breaststrokers for the free swimming and start and turn race components to reveal the relative strengths and weaknesses of GB breaststroke swimmers.

This research will provide quantitative evidence to substantiate the perceived discrepancy between GB and international swimmers, from the start and turn abilities of other nations and to confirm whether increased research and interventions to improve the skills performance of GB breaststrokers are warranted.

3.2 Method

Prior to the commencement of race analysis at a competition, a calibration of the swimming pool is undertaken. This involves aligning the coloured plastic disc markers across all the lane ropes to set distances and then placing clamps on the lane ropes to hold them in place for the entirety of the competition. Multiple photos of the lane ropes are then taken to create a composite image where calibration lines are drawn to identify the key distances that are used in the analysis. These are: 5 m; 10 m; 15 m; 25 m; 35 m and 45 m (Figures 3.1 and 3.2). At major competition lane ropes are manufactured by Malmstein (Malmstein) where the width of each marker is 8cm on. The disc marker width is used as a calibration object when calculating non-fixed distances such as breakout distances.

5 m	15 m	25 m	35 m	45 m

Figure 3.1: Composite image of the swimming pool with calibration lines drawn across the lane ropes to identify the key distances.

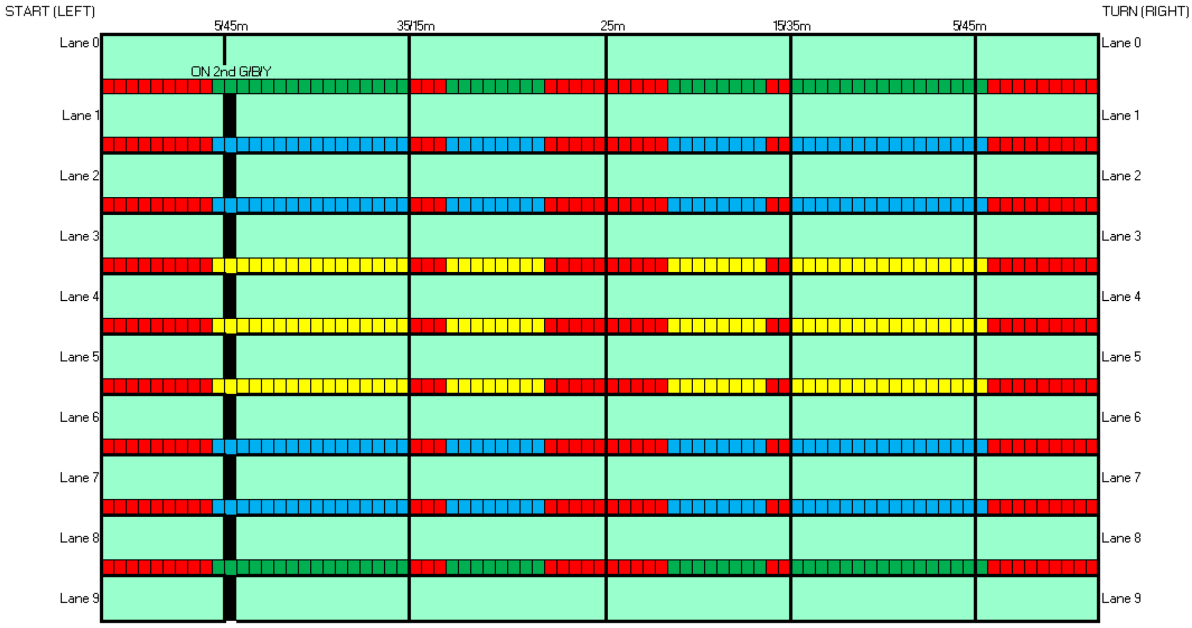


Figure 3.2: A schematic image derived from figure 3.1.

Start time was defined as the period from when the starting signal is triggered (gun time) to the swimmer's goggle strap line on the head reaching 15 m. Turn time was defined as the period from the first visible hand touch of the wall with two hands simultaneously, to the swimmers' goggle strap line on the head reaching 15 m. Finish was defined as the last 5 m of a race. Free swimming is considered as all segments of the race not included in the start, turns and finish.

Race analysis data were obtained from the British Swimming NEMO database for all Long Course European Championships, World Championships and Olympics Games, between 2015 and 2020. This consequently included 1 Olympic Games, 2 Commonwealth Games, 2 European Championships and 3 World Championships. Specifically, race time, start time and turn time data for the men's and women's 50 m, 100 m and 200 m breaststroke events were exported. Total turn time was also calculated for the 200 m breaststroke where multiple (three) turns are completed. The analysis focussed on these competitions as they are the major competitions in the swimming event calendar and acknowledged as being the most competitive.

The data were divided into event and sex and then organised into a database where the fastest recorded start time and turn time of each GB and international swimmer in the database were identified. These times were recorded in World

Championships, European Championships and Olympics from between 2015 to 2020. This resulted in a sample of 122 race performances (n=58 male, n=64 female) (Table 3-1). The fastest recorded start and turn times from all international swimmers in the database were identified to allow GB swimmers to be compared to: 1) the fastest starters and turners in the world, 2) the fastest race performers in the world.

Table 3-1: A gender and nationality breakdown of the sample analysed in this study.

Event	Male GB	Female GB	Male non-GB	Female non-GB
50	4	6	14	13
100	6	7	12	15
200	6	4	16	19

Shapiro–Wilk test found the fastest recorded start time and turn time of each GB and international swimmer in the database did not meet the required assumptions therefore Spearman rank correlation coefficients were calculated to establish the strength of association between the male and female breaststroke swimmers' start and turn times and their overall race time in each breaststroke event.

A correlation was considered significant if $P < .05$. Correlations were defined as follows: weak, <.4; moderate, .4 – .6; or strong, >.6 (Mukaka, 2012). In addition to correlations, descriptive statistics including mean, range and standard deviations were displayed and a percentage difference was calculated between GB and international swimmers for starts, turns and free-swimming speed. Percentage differences were also calculated between GB swimmers and non-GB swimmers.

3.3 Results

Table 3-2: Spearman ranks correlation coefficients between start time and race time for 50, 100 and 200 m male and female breaststrokers.

Event (m)	n	Sex	Correlation Coefficient	p
50	18	Male	.45	.63
	19	Female	.73**	.00
100	18	Male	.46	.06
	22	Female	.51*	.02
200	22	Male	.36	.11
	23	Female	-.03	.90

*. Correlation is significant at the .05 level (2-tailed).

**. Correlation is significant at the .01 level (2-tailed).

Table 3-2 shows that start time has a strong positive correlated to race time for the female 50 m breaststroke (r= .73, p< .00) and a moderate positive correlation for female 100 m breaststroke (r= .51, p= .02). No association was found between the start time and race time of the male 50 m, 100 m and 200 m or for the female 200 m breaststroke swimmers.

Table 3-3: Spearman rank correlation coefficients between mean turn time, turn 1, 2 and 3 and race time for 100 m and 200 m Male and Female Breaststroke.

Event (m)	Sex	Mean	Turn 1	Turn 2	Turn 3
100	Male	.62*	.62*	-	-
	Female	.27	.27	-	-
200	Male	.72*	.67*	.65*	.62*
	Female	.48*	.33	.60*	.41*

*. Correlation is significant at the .05 level (2-tailed).

**. Correlation is significant at the .01 level (2-tailed).

Table 3-3 shows that mean turn time is strongly correlated to race time for the male 100 m and 200 m breaststroke (r= .62, p= .002 and r= .72, p<.001) and moderately correlated for the female 200 m breaststroke (r= .48, p< .02). No association was found between the mean turn time and race time in the female 100 m breaststroke swimmers. Additionally, all three turns separately were found to have a strong positive correlation to race time for the men's 200 m breaststroke (r= .62 - 67, p< .001) with only turn 2 having a strong positive correlation (r= .60, p= .002) and turn 3 moderate positive correlation for the women's 200m (r= .41, p= .049). No association was found between turn 1 and race time in the women's 200 m breaststroke.

Table 3-4: Spearman rank correlation coefficients between start time and mean turn time for 100 m and 200 m Male and Female Breaststroke.

Event (m)	Sex	Correlation Coefficient	pp
100	Male	.79**	<.001
	Female	.48*	.02
200	Male	.4	.08
	Female	.31	.16

*. Correlation is significant at the .05 level (2-tailed).

**. Correlation is significant at the .01 level (2-tailed).

Table 3-4 shows that start time was found to have a strong positive correlation to mean turn time for the men's 100 m (r= .79, p< .001) and moderately correlated for the women's 100 m breaststroke (r= .48, p= .02) however no association was found between the start time and mean turn time for men's or women's 200 m breaststroke.

Table 3-5: % drop off in turn time from 1st to 2nd, 2nd to 3rd and 1st to 3rd turn for the 200 m Male and Female Breaststroke.

Event (m)	Sex	%Δ turn 1 to 2 (%)	% Δ turn 2 to 3 (%)	% Δ turn 1 to 3 (%)
200	Male	20.6	5.2	25.9
	Female	12.0	20.1	32.1

Table 3-5 identifies a % decrease across all three turns with the male and female 200 m breaststroke. A consistent % drop off in turns performance of 12.0% and 20.1% was found between turns 1 and 2 and 2 and 3 respectively for the women. A larger difference was found from turn 1 to 2 of 20.6% in comparison to 5.2% between 2 and 3 for the 200 m male breaststrokers.

Table 3-6: Descriptive statistics including median, range and interquartile range for race time, start time and mean turn time for GB and international swimmers fastest recorded time for starts, turns and free-swimming speed.

Event (m)	Sex	Sample	n	Race time (s)	Start time (s)	Free Swim time (s)	Mean turn time (s)
50	Male	non-GB	14	26.86 ± 0.23 (26.52 - 27.36)	6.13 ± 0.35 (6.02 - 6.52)	20.77 ± 0.32 (20.12 - 21.07)	na
		GB	4	27.36 ± 1.48 (26.06 - 28.00)	6.58 ± 0.50 (6.2 - 6.76)	20.75 ± 1.11 (19.86 - 21.26)	
50	Female	non-GB	13	30.31 ± 0.64 (29.84 - 31.23)	7.44 ± 0.41 (7.08 - 7.74)	22.98 ± 0.48 (22.44 - 23.85)	na
		GB	6	31.05 ± 1.66 (30.05 - 32.18)	7.38 ± 0.33 (7.34 - 7.88)	23.33 ± 1.27 (22.71 - 24.42)	
100	Male	non-GB	11	59.11 ± 0.52 (58.59 - 59.96)	6.32 ± 0.23 (5.73 - 6.52)	43.91 ± 0.61 (43.52 - 44.63)	8.81 ± 0.35 (8.22 - 9.14)
		GB	6	59.76 ± 2.95 (57.10 - 61.98)	6.60 ± 0.34 (6.38 - 6.86)	44.13 ± 2.04 (41.85 - 45.92)	8.97 ± 0.41 (8.75 - 9.21)
100	Female	non-GB	15	66.42 ± 0.91 (64.13 - 67.18)	7.6 ± 0.6 (7.16 - 8.08)	48.72 ± 0.70 (47.21 - 49.22)	9.97 ± 0.35 (9.60 - 10.25)
		GB	7	67.5 ± 1.40 (66.81 - 68.68)	7.68 ± 0.14 (7.46 - 7.82)	49.67 ± 0.66 (48.97 - 51.12)	10.07 ± 0.36 (9.51 - 10.23)
200	Male	non-GB	16	128.39 ± 1.58 (126.68 – 130.51)	6.4 ± 0.34 (6.18 – 7.00)	93.86 ± 1.11 (92.1 - 95.18)	9.24 ± 0.25 (8.88 - 9.71)
		GB	6	130.59 ± 3.4 (128.52 - 132.88)	6.7 ± 0.38 (6.42 - 6.80)	94.73 ± 1.64 (93.11 - 98.03)	9.45 ± 0.38 (9.20 - 9.57)
200	Female	non-GB	19	142.64 ± 1.29 (139.64 - 146.62)	7.9 ± 0.4 (7.24 - 8.16)	103.68 ± 2.41 (100.92 - 106.19)	10.46 ± 0.40 (10.10 - 10.85)
		GB	4	144.46 ± 2.78 (143.42 - 146.50)	7.77 ± 0.29 (7.58 - 7.94)	104.1 ± 0.73 (103.79 - 104.58)	10.32 ± 0.34 (10.18 - 10.58)

Table 3-7: Percentage difference between GB and international swimmers fastest recorded time for starts, turns and free-swimming speed.

Event (m)	Sex	Sample	n	%Δ Free swim (%)	%Δ Start time (%)	%Δ Mean turn time (%)
50	Male	non-GB	14	-0.1	7.3	n/a
		GB	4			
	Female	non-GB	13	1.5	0.8	n/a
		GB	6			
100	Male	non-GB	11	0.5	4.4	1.8
		GB	6			
	Female	non-GB	15	1.9	1.1	1
		GB	7			
200	Male	non-GB	16	0.9	4.7	2.3
		GB	6			
	Female	non-GB	19	0.4	-1.7	-1.34
		GB	4			

In the 50 m breaststroke event, the male GB swimmers' race times were, on average, 0.5 s slower than the international swimmers, with their free-swimming component of the race being 0.1% faster; their start times were, on average, 7.3% (0.45 s) slower. The female GB swimmers' race times were, on average, 0.74 s slower than the international swimmers, with their free-swimming component of the race being 2.4% slower; their start times were, on average, 0.8% (0.06 s) slower (Table 3-6 and 3-7).

In the 100 m breaststroke event, the male GB swimmers' race times were, on average, 0.65 s slower than the international swimmers, with their free-swimming component of the race being 0.5% slower; their start times were, on average, 4.4% (0.28 s) slower; their turn times were, on average, 1.8% (0.16 s) slower. The female GB swimmers' race times were, on average, 1.08 s slower than the international swimmers, with their free-swimming component of the race being 1.9% slower; their start times were, on average, 1.1% (0.08 s) slower; their turn times were, on average, 1% (0.1 s) slower (Table 3-6 and 3-7).

In the 200 m breaststroke event, the male GB swimmers' race times were, on average, 2.2 s slower than the international swimmers, with their free-swimming component of the race being 0.9% slower; their start times were, on average, 4.7% (0.3 s) slower; their turn times were, on average, 2.3% (0.21 s) slower. The female GB swimmers' race times were, on average, 1.82 s slower than the international swimmers, with their free-swimming component of the race being 0.4% slower; their start times were, on average, 1.6% (0.13 s) faster; their turn times were, on average, 1.3% (0.14 s) faster (Table 3-6 and 3-7).

3.4 Discussion

3.4.1 Relationship between starts, turns and race performance

The first aim of this study was to determine the strength of association between breaststroke swimmers' start and turn times and overall race time in each breaststroke event, to highlight the importance of start and turns in a breaststroke race.

The main findings were that start time was found to be significantly correlated to race time in the 50 m and 100 m women's breaststroke events. A strong correlation was solely found in the women's 50 m breaststroke whereas moderate correlations were found for all remaining events where correlations were identified. The events where start time was not significantly correlated to race time were male 50 m, 100 m and 200 m or for the female 200 m breaststroke swimmers.

These results are supported by Mason and Cossor (2000) and Thompson, Halkand and MacLaren (2010), who also found strong correlations in the 100 m women's breaststroke (r= .76, r= .89 respectively). Contradictory to this study, strong correlations were found by Olstad *et al. (*2020) and Thompson, Halkand and MacLaren (2010) who also reported a strong correlation (r = .979, r = .87 respectively) between the start time and final race time of the men's 100 m breaststroke with Mason and Cossor (2000) finding a moderate correlation (*r= .59*). Additionally, strong correlations were also found by Mason and Cossor (2000) and Thompson, Halkand and MacLaren (2010) in the 200 m men's breaststroke (r= .62, r= .85 respectively). Results from this study in the women's 200 m breaststroke are supported by Mason and Cossor (2000), who also found no correlation. A limitation of Mason and Cossor's research was they did not analyse the 50 m breaststroke events and therefore no comparable data are available.

Mean turn time was found to have a strong correlation with race time in all men's breaststroke events (100 m and 200 m) and a moderate correlation in the 200 m women's breaststroke events. The only event where mean turn time was not significantly correlated to race time was in the women's 100 m breaststroke. These results are supported by Mason and Cossor (2000), who also found turn times to have a strong correlation with race time in the men's 200 m (r= .67) and Thompson, Halkand and MacLaren (2010) in the 100 m (r= .84) and 200 m men's (r= .94) event. However strong correlations were also found by Mason and Cossor (2000) and Thompson, Halkand and MacLaren (2010) in the 100 m women's breaststroke (r= .82, r= .84), 200 m women's (r= .91, r= .96) and 100 m women's (r= .92) by Thompson, Halkand and MacLaren (2010) yet only a moderate correlation was found for the male 100 breaststroke (r= .53) women's 100 m events (r= .92) by Cossor and Mason (2010). Furthermore, a statistically significant positive correlation between turn time and final race time in the 100 m (r = .960 - .929) and 200 m breaststroke (r = .851 - .984) was found by McCabe *et al. (*2022) This agrees with Sánchez *et al.* (2021) and Olstad *et al.,* (2020) who also found that turn time was strongly associated with final time in both genders and events (r = .706 - .931) and in male 100m (r = .829) respectively in short course swimming.

A reason that different correlation strengths are being found between this current study and previous research may be due to the sample used. Cossor and Mason (2000), McCabe *et al. (*2022) and Thompson, Halkand and MacLaren (2010) all included finalists in Olympics and/or World Championships ranging from 1992 – 1999 (Thompson, Halkand and MacLaren, 2010;) Cossor and Mason, 2000) and 2015-2019 (McCabe *et al*., 2022) however this study focused on the personal bests of all GB and international swimmers when calculating correlations between starts, turns and race times which consequently only allowed for one data entry per swimmer per event providing a smaller sample size than the other studies. It is possible that this homogeneous sample affected the magnitude of the correlation coefficient.

In addition to finding a strong correlation between mean turn time and race time in the 200 m event for both genders, Thompson, Halkand and MacLaren (2010) found that when broken down into each of the three turns, women maintain a strong correlation throughout (r= .92 - .95) in comparison to the men where only the first of the three turns was highly correlated with race time (1st turn; r = .90, 2nd turn; r= .46, 3rd turn; r= .38). An opposing trend was found in this study with all three male 200 m turns being found to be strongly correlated to race time whereas only the second was strongly correlated and third turns moderately in the women's 200 m breaststroke. It is possible that as a result of better technical ability or faster approach speeds (resulting in faster exit speeds) the male swimmers turn contribute to stronger correlations to race time.

In the male 200 m breaststroke event, on average there was a 25.9% decline in turn performance between turns 1 and 3. The largest contribution to this being displayed between turns 1 and 2 where a 20.6% drop in turn time was observed and only a 5.2% drop off between turns 2 and 3. This differed for the women's 200 m breaststroke as, although a larger decrease in turn performance was observed (32.1%) there was a consistent decrease in turn performance between turn 1 and 2 and 2 and 3 (12.0% and 20.1%). Multiple variables could affect these differences observed from pacing of the race to fatigue. Potentially women pace their race with a more even split throughout whereas some men may commence their race with more pace within the first 100 and consequently their first turn is performed much faster than the other two turns (Thompson, Halkand and MacLaren, 2010).

3.4.2 Relationship between starts and turns

In addition to highlighting the strength of association between breaststroke swimmers' start and turn times and overall race time in each breaststroke event this study found that start and mean turn time was found to have a strong correlation in men's and women's 100 breaststroke events. However, no association was found between the start time and mean turn time for men's and women's 200 m breaststroke. This demonstrating that in the 100 m events those with the quickest starts may also have the quickest turn times however in the 200 m events those swimmers who are the quickest starters are not as a consequence the best turners. Therefore, starts and turns should be identified as separate skills and require specific, dedicated training and time on each.

3.4.3 Comparison of GB breaststrokers to World Leading breaststrokers

The second and third aims of this study were to compare personal best (PB) start and turn times of GB breaststroke swimmers to those of their international counterparts and to establish the relative difference between GB and international breaststrokers for the free swimming and start and turn race components to reveal the relative strengths and weaknesses of GB breaststroke swimmers.

The main findings were that in the 50 m breaststroke, the best start time median value for GB men was 0.45 s slower than the best start time median value for non-GB breaststrokers and 0.06 s slower for the GB women. In comparison, in the free-swimming component of the race GB male swimmers were 0.1% faster than non-GB swimmers. In contrast, GB female 50 m breaststroker swimmers were slower than their international counterparts during both starts and free swimming. However, the 0.06 s difference between GB and non-GB women's start times is the smallest starts difference across all events indicating that only marginal improvements need to be made by GB women in the 50 m breaststroke in this study to be aligned with all other international swimmers. Overall, this highlights that for the 50 m breaststroke event the perception that Great Britain (GB) swimmers are relatively poor on their starts compared to their free-swimming ability is correct, for both males and females.

To put these findings into some context, the three medallists in the women's 50 m breaststroke at the 2019 World Championships finished within 0.31 s of each other. At the same Championships, the men's 50 m breaststroke bronze medallist was only 0.03 s behind the silver medallist. Specifically, for a Great Britain swimmer the gold medal in the 2018 Commonwealth Games men's 50 m breaststroke was lost by 0.04 s. If the British Swimmer has the capacity to potentially make up to a 0.38 s improvement on starts it would have given GB the gold medal.

In the 100 m breaststroke a difference of 0.28 s and 0.08 s was found for start time between GB and non-GB PBs in the men's and women's event respectively. This highlighted that for start time in the 100 m breaststroke, GB swimmers were slower to 15 m than non-GB swimmers. When focusing on total turn time both GB men and women were also slower by 0.16 s and 0.1 s respectively to their non-GB counterparts.

Although it was also identified that male GB swimmers were slower in the free swim component of the race, a smaller percentage difference was present in comparison to starts and turns in the men's event. This differed to the women's event as free swimming was found to have the greatest percentage difference between GB and non-GB swimmers over starts and turns. This highlights that GB male swimmers have a greater loss during starts and turns in comparison to free swimming than other international swimmers whereas women have a greater loss during the free swim segment.

For the men's 200 m breaststroke GB swimmers were found to be 0.3 s and 0.21 s slower than non-GB swimmers for start time and mean turn time, respectively. In addition to male GB swimmers being slower in starts and turns men's 200 m breaststrokers were 0.9% slower than their international competitors in the free-swimming component of the race.

The only event within this study where GB breaststrokers were faster than non-GB swimmers on both their start and mean turn times was the women's 200 m breaststroke. On average, these GB swimmers were 0.13 s quicker on start time and 0.14 s quicker for mean turn time. In contrast, the GB women were 0.4% slower at free swimming in the 200 m event indicating that GB female swimmers do not lose time on the start and turn elements in comparison to non-GB swimmers however are slower in the free-swimming component of the race. A potential reason for this could be that all GB female swimmers included in this database are from an individual medley background and could potentially have the ability to transfer skills such as efficient fly kick and high elbow catch positions into their underwater pull-outs. These results do not support the perception that GB breaststrokers have relatively poor start and turn performances.

A limitation to this study was the exclusion of breakout distance as a metric. Unfortunately, due to the data being collected prior to the thesis breakout distances were not available for all data entries and therefore a decision was made to exclude it entirely as a metric. If further research was to be completed breakout distance should be included as it will give further insight into to understand whether breakout distance is contributing to faster start and turn times by international breaststrokers.

3.5 Conclusion

This study found that start time was correlated to race time in the women's 50 and 100m events, however no correlation was found in the women's 200m or any men's events. In addition, turn time was found to be correlated to race time for the men's 100 m and 200 m breaststroke with all turns separately correlating to race time in the 200m. Turn time was also found to be correlated in the women's 200 m, however only turns 2 and 3 were correlated when separated. For the men's 200 m event there was found to be an average 25.9% drop off between turn 1 and 3 with a 32.1% drop in the women's 200 m. Within the men's and women's 100 m start time was also correlated to turn time however this was not the case in the 200 m for either gender.

The Men's 50 m breaststroke was the sole event where GB swimmer's free-swimming was faster than non-GB swimmers. However, in the men's 100 m the percentage difference for the free swim was less than for starts/turns, showing that GB swimmers in these events are further away from their international counterparts in start and turn elements than the free swimming. Consequently, there is a large improvement that can be made to GB breaststrokers' starts and turns which could be the determining factor between winning a gold Olympic medal and not.

4 Chapter Four: General Methods

4.1 General Methods

4.1.1 Participants

Participants were recruited though the British Swimming Performance Centre in Loughborough and the Loughborough University Performance squad. All swimmers had experience of swimming breaststroke at a national level as a minimum standard.

From this participant sample, elite and sub-elite samples were identified. In this thesis elite and sub-elite samples were not defined on the swimmer's race time or their start time (s) to 15 m in competition, they were defined specifically on their ability to best perform the BUP and consequently were those who completed the BUP to 10 m in the fastest time. 10 m time was identified as the most accurate representation of BUP performance as all participants had completed their breakout prior to this distance. Two distinct groups were found. The elite sample comprised 7 swimmers (mean 10 m time; 5.35 s) who had competed at international level (mean FINA points = 932). The sub-elite sample comprised 14 swimmers (mean 10 m time; 6.00 s; mean FINA points = 932).

4.1.2 Data Collection

Anatomical markers are skin mounted markers used to highlight the location of key anatomical landmarks, such as the lateral and medial femoral condyle to identify the knee joint centres. This enables researchers to record the movement of the markers and determine the movement of the underlying bone structures (Payton and Burden, 2017). Throughout this research all markers were circular markers drawn on the anatomical landmarks in permanent marker; this eliminates the effect 3D markers would have on drag, the potential altered body mechanics and the additional time constraints of reapplying markers that have been lost during the trials (Kjendlie and Olstad, 2012).

In total, 28 anatomical markers were used to create a full body marker set for all trials (Figure 4.1a and 4.1b). The anatomical markers were located on the left and right acromia, medial and lateral epicondyles of the humerus, styloid processes of the radius and ulna, right and left greater trochanter, lateral epicondyles of the tibia, lateral malleolus, the most distal point of the 2nd phalange (index finger) and the distal phalange of the Hallux. Four further markers were applied, two were drawn at the head of the humerus when the swimmer was standing in a streamline position (Figure 4.1b), two at the head of the humerus when standing in an anatomical position (Figure 4.1a)

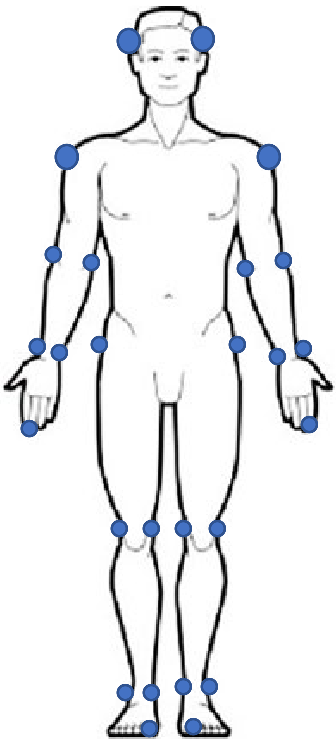


Figure 4.1a

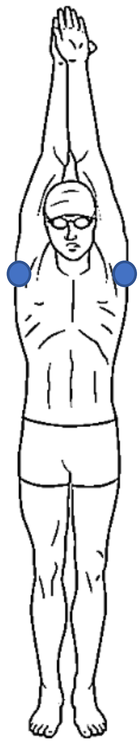


Figure 4.1b

Figure 4.1: Full body marker placement diagram

4.2 Equipment

4.2.1 3D video capture system

Eight standard POI (GigE) cameras (Stemmer Imaging, Mako G-223B, Surrey, UK) with full HD resolution (2048 x 1088) in underwater housings (Autovimation Nautilus IP68) were submerged to a depth of 1 m on weighted tripods and positioned to maximise the field of view of the swimmer underwater. Two identical controlling PCs were used, each controlling four cameras that were connected through high-speed transfer ethernet cables to a controlling PC. All underwater cameras were trained and focused on the calibrated volume (Figure 4.2). The camera settings such as shutter speed for exposure were adjusted accordingly for the change in light present using the recording software (Geko GigE video recorder v1.9.4, Vision Experts Ltd, Surrey, England). The capture frequency of each camera was set to 50 Hz and the shutter speed to 1/500 s as Payton (2008) stated that a range of 25-50 Hz and 1/350 to 1/750 s is appropriate for swimming. The exposure time was continually adjusted to accommodate the changing natural light levels on the pool. The aperture was set at f/2.8 to avoid an overexposed image and a wide-angled lens was used.

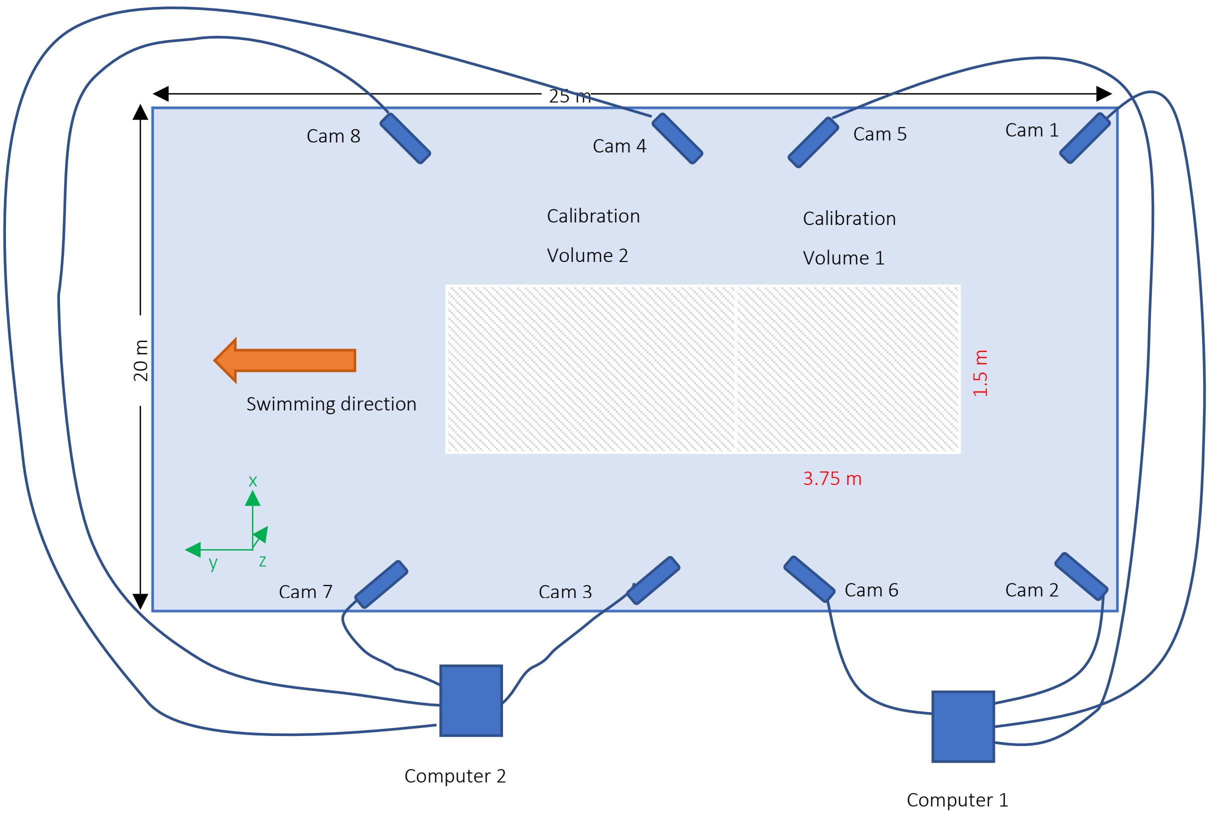


Figure 4.2: Plan view of experimental set up for 3D motion capture of swimmer

A calibration frame constructed from vertical and horizontal poles, floats and 60 spherical control points with accurately measured distances was used to create a calibrated volume in the centre of lane 4 (Figure 4.2). The dimensions of the calibration frame were (1.50 m x 6.15 m x 1.20 m). As the dimensions of the frame were not sufficient to fill the required volume for this study (and the field width of the cameras was ~7 m) two calibrations were completed as follows:

4.2.2 Calibration

Calibration Volume 1 - dependent on the data collection session, the calibration frame was positioned 2.48 m, 2.68 m or 2.69 m from the end wall. A laser measure was used to record the frame's location (± 1mm) from the side and end of the pool. All measurements were repeated three times. The frame was recorded in this location from all four cameras – this was designated Calibration 1.

Calibration Volume 2 - the calibration frame was then translated 2.68 m in the swimming direction (y-axis) to extend the calibration volume. Laser measurements were used to ensure that the frame's position along the x-axis remained unchanged. The frame was then recorded again from all four cameras – this was designated Calibration 2.

In total, the calibrated volume measured 1.50 m x 10.10 m x 1.2 m with a 1.067 m overlap between calibrated volumes 1 and 2 in the y direction. The y-axis was directed down the pool in the swimming direction, x-axis directed horizontally to the right wall of the pool and the z-axis directed vertically upwards.

4.2.3 Speed reel

The speed reel system was designed by Southampton University to directly measure a swimmer's speed. The system works by measuring the rotational speed of a wheel and converts it to the linear speed of the cable via the known radius of the wheel ($v = r\omega$) at a sampling frequency of 250 Hz as the swimmer progresses. The speed reel is placed on the end of the pool that the swimmer pushes off from. The line is guided through a wall mounted pulley system set at a depth of 0.7 m and then fastened to a belt worn around the swimmer's waist. The line is placed on the small of the back for breaststroke to avoid the swimmer kicking the line during trials. Throughout all data collections the speed reel was placed at the fixed end of the pool, from which all trials commenced, proximate to the starting block in lane 4. Through previous use within the Performance Centre, this placement was used to avoid the swimmer kicking the line during breaststroke trials. As the studies focused on the underwater breaststroke phase, the line was guided through a wall mounted pulley system set at a depth of 0.7 m. As the speed reel also measures the distance that the swimmer travels, the calibration of the speed reel is based on distance and was completed prior to testing. This consisted of the lead researcher manually pulling the line on land to known distances based on a tape measure that had been placed alongside. Each key distance of 2.5 m, 5 m, 10 m and 15 m was measured and recorded 10 times so ensure reliability of the calibration. The coefficient of variation (CV) was then calculated to show the level of dispersion around the mean with a lower value of the coefficient of variation, the more reliable the calibration. Any value lower than 0.5% was deemed reliable.

4.3 Procedures undertaken for studies 3, 4, and 5.

4.3.1 Experimental Protocol

The participants completed two trials comprising a push off from the wall, completion of a BUP including breakout and one full stroke cycle on the surface. One full stroke cycle was included to extend the trials to reduce the swimmer slowing to finish the trial, affecting the underwater phase. The participant was asked to push off the wall with maximum effort and to perform the BUP exactly how they would within a race to increase the repeatability of trials. Two trials were selected as the repeatability of elite/trained swimmers performing a known skill has been evidenced by Vantorre *et al. (*2010) who stated that a high reproducibility of flight, leg kicking, swimming and underwater phases of a start were evident in starting performance of trained swimmers. Due to the maximal efforts of each trial, minimal repetition was decided to reduce the impact on the swimmer.

Video and speed reel data were captured for all trials. Post data collection, all video files were converted from RAW files into video files compatible with Simi Motion (8.5.5) and imported into SIMI Motion 3D where manual digitisation was completed.

Due to the requirement for maximal effort trials and the consequent potential for fatigue, a compromise was made that all swimmers would complete their BUP from a push, with a smaller number also completing a start. This was completed to increase the number of participants included within the thesis. The participants who completed the BUP from both a push and start were selected by the coaches based on the training load that swimmer had accumulated in the week prior to testing. If too high only the BUP from a push was completed. Additionally, for the participants who performed both start and wall push offs, a statistical analysis between the temporal parameters of a BUP from a start and a push was undertaken.

4.3.2 Digitising

The calibration control points were digitised using in SIMI Motion 3D to create the known distances throughout the calibrated volume.

A combination of automatic and manual tracking was performed for all eight camera views for one trial using SIMI Motion 3D. As the BUP is a complex three-dimensional movement automatic tracking was only effective on the hip, knee and ankle markers in the 1st glide phase. All other markers were manually digitised from the initiation of the fly kick preparation phase to breakout (defined as the separation of the hands as the head breaks the surface of the water).

Deleva's CoM model was selected as both female and male body segment parameter data is included whereas a gender bias was identified within other models, as only male data was included (de Leva, 1996). In addition, van der Westhuizen (2021) found that although model selection had a significant effect on intracycle measurements of horizontal velocity, it was unlikely to affect differences in measurements between underwater fly kick cycles (van der Westhuizen, 2021).

4.3.3 Data Processing

Once all anatomical markers were digitised, a quintic spline was applied and the 3D co-ordinates of the markers were reconstructed for calibration volume 1 and then calibration volume 2 using a 3D Direct Linear Transformation. A quintic spline was used as an alternative to a butterworth filter, as endpoint errors with a butterworth filter made splicing two sets of data together problematic. A quintic spline was identified as the preferred filter in order to avoid distortion of the start and end of data sets (Zin et al., 2020).

4.3.4 Statistical Analysis

Throughout the thesis a Multivariate analysis of variance (MANOVA) was completed to identify differences of multiple dependent variables between: 1) the separated versus overlap technique; 2) elite versus sub-elite samples (skill level); and

3) dive entry versus wall push-off. A MANOVA was selected due to its ability to examine multiple dependent variables simultaneously and therefore reducing the chance of making a Type I error (Field, 2009). F, Hypothesis df, Error df, p value, Wilks' lambda value and Partial Eta Squared effect sizes were then reported.

Additionally, multiple correlations were completed within this thesis to establish the strength of association between 10 m time and the chapter specific variables. Spearman rank correlation coefficients and Pearson correlation coefficients were both completed dependent on the findings of the Shapiro–Wilk test identifying if the data met the required assumptions or not. Correlations were considered significant if $P < .05$. Correlations were defined as follows: weak, <.4; moderate, .4 – .6; or strong, >.6 (Mukaka, 2012).

4.4 Ethical Considerations

4.4.1 Recruitment, informed consent and anonymity and confidentiality

Potential participants were approached in person by the lead researcher, given a participant information sheet and consent form and were invited to ask any questions before agreeing or disagreeing to participate in the research.

Before participating in the research, all participants received an information sheet and consent form explaining everything that was required of them, the security of their data and ability to withdraw at any point throughout the research without reason. A signature was provided to confirm written consent to participate in the research.

All data were anonymised to eliminate participant identifiers. All participant information including identifiers were kept on a separate spreadsheet, to which only the lead investigator and supervisory team had access. The lead investigator, supervisory team and British Swimming staff including the coach and sports science and sports medicine staff will have access to the data however only with written permission from the participant.

All data will be kept on a password protected appropriate laptop and on an encrypted portable device during the thesis and further to this will be kept on a British

Swimming password protected computer which sports science staff will have access to. There is no deletion date planned for this data.

All data collection procedures were approved by MMU Cheshire's Department of Exercise and Sport Science Ethics Committee.

5 Chapter Five: Comparison of two methods of measuring instantaneous speed during the underwater pull-out in breaststroke

5.1 Introduction

Video analysis is commonly used for quantitative and qualitative analyses of aquatic sports such as swimming. Two-dimensional video protocols are commonly used to collect kinematic information to analyse swimmers' start and turn characteristics and stroke mechanics; three-dimensional protocols are less common. In previous research both static cameras (above and below water level) (Vantorre *et al*., 2011), moving cameras attached to a trolley (Seifert *et al*., 2010) or a combination of the two (Oxford *et al*., 2016) have been used to capture video recordings.

The evaluation of mean speed and intra-cyclic swimming speed has been highlighted as a useful tool to assess swimming economy and overall performance (Figueiredo *et al*., 2011). There are several popular approaches to determining speed within swimming. The most common involves digitising one or more points on the swimmer's body, from sequential video images, to obtain 2D or 3D coordinates and then computing the speed from those coordinates (de Jesus *et al.,* 2012; Veiga, Cala, Frutos and Navarro, 2014). The second most common approach is to measure speed directly using a device such a velocity meter or speed reel (Gourgoulis *et al*., 2018).

The majority of swimming kinematics studies use two-dimensional analysis (e.g., Seifert, Vantorre and Chollet, 2006; de Jesus *et al*., 2012; Veiga, Cala, Frutos and Navarro, 2013). It is a less time-consuming method than 3D video analysis, there is a greater accessibility to equipment due to low equipment costs and quick feedback is achievable with simpler data analysis. 2D video analysis is regularly used by coaches for qualitative analysis (Callaway, 2015). However, there are several limiting factors with this approach: often bilateral symmetry is falsely assumed due to acceptance that the movement being analysed is confined to a single, pre-defined plane. Also, perspective errors exist when movements occur outside this plane (Payton and Bartlett, 2017. The swimming strokes are not planar activities and must be viewed in three-dimensions to truly represent the motion of the whole body (Psycharakis *et al*., 2005). Additionally, rotation cannot be calculated from a single plane 2D video analysis and could contribute to the appearance of 2D sagittal kinematics (Schurr, Marshall, Resch and Saliba, 2017). 3D video analysis is a more accurate method than 2D analysis as it eliminates the perspective error inherent in a 2D analysis and the incorrect representation of joint angles; it allows the true spatial movements of the performer to be quantified (Payton and Bartlett, 2008).

When comparing CoM speed and speed from a velocity meter, it was identified that during breaststroke free swimming the hip centre intracyclic speed overestimates maximal values and underestimates minimal values, in comparison to centre of mass speed. Gourgoulis *et al*., (2018) stated that this was due to intersegmental actions of the arms and legs affecting CoM speed with the forward displacement of the upper and lower limbs throughout the arm and leg recovery causing the CoM to decelerate less than the hip and the backward movement of the legs during the kick affecting CoM speed.

Although data processing is time consuming and systematic and random errors can be caused through manual digitisation (Wilson *et al*., 1999; Mooney *et al*., 2015a) within swimming this method is a more appropriate choice than the laboratory condition 'gold standard' of three-dimensional optoelectronic analyses (Payton, 2008). Contrast between the reflective markers and the background and turbulent water can obscure the markers and introduce additional error in automatic procedures (Payton, 2008). An increase in drag and reduction in performance has also been found as a result of the reflective markers (Washino *et al.*, 2019) with Kjendlie and Olstad (2012) reporting an increase of 7% to 10% in passive drag when wearing a typical set of 24 markers of 19 mm diameter.

A further development in this field more recently is the use of markerless technology (Ascenso *et al*., 2020). This removes the requirement for markers to be applied to swimmers or the lengthy process of digitisation. Markerless technology requires the automatic extraction of the contour (the silhouette) of the swimmer, and the locations of the swimmer's joints (referred to as 2D joints) in camera coordinates, this however is at the forefront of swimming research and is yet to be accomplished without error (Ascenso *et al*., 2020).

As an alternative to video-based measurement systems, 'velocity meters' are a quick and affordable way of assessing the instantaneous speed of a swimmer. Velocity meters are commercially available e.g., the Swim speedometer (Swimsportec®, Hildesheim, Germany) and have been validated against 2D video-based measures of hip speed by several researchers (Feitosa *et al*., 2013; Morouco *et al*., 2006). Feitosa *et al*. (2013) found that, compared to 2D hip velocity obtained from a single sagittal camera, a velocity meter met all validation criteria (paired Student's t-test, linear regression models and Bland-Altman plots). They concluded it was an appropriate device to assess human horizontal intra-cyclic velocity, specifically when completing breaststroke and butterfly strokes.

The connection of the line to the swimmer however does presents practical limitations as the swimmer can involuntarily kick the line during swimming causing errors within the recorded speed of the swimmer (Vilas – Boas *et al*., 2011). Furthermore, to enable the line to remain tight during deceleration of the swimmer, a constant resistance is added to the cord, consequently, this is constantly applied to the swimmer (Dadashi, Crettenand, Millet and Aminian, 2012).

The CoM obtained from 3D video analysis is assumed to provide the most accurate measure of the speed of the whole swimmer and could be considered the gold standard criterion against which methods should be compared. However, as the video digitisation of a hip marker and speed reel both determine the speed of a fixed point on the body, they will not produce the same speed-time profile as that of the CoM. Therefore, any differences between the three data sets should not be considered as errors (true value – measured value) as each approach could be providing an equally accurate measure of what it is intended to measure. Knowing how the speed reel output and speed derived from a fixed point (hip) differ from the CoM speed will provide a better understanding of how to interpret swimmer speeds obtained using these methods. This study will differ from previous studies as it will compare speed reel to both mid-hip and 3D CoM speed collected throughout the BUP.

The aim of this chapter is to compare speed variables for the breaststroke underwater phase, obtained from the speed reel system, to the same variables derived from: a) 3D coordinates of a fixed marker on the hip; and b) CoM obtained through 3D video analysis.

5.2 Methods

Specifically, for this study, the mid-hip centre was calculated as the mid-point between the right and left greater trochanters. The speed of the mid-hip and Centre of Mass speed were calculated from the instant the entire swimmer was visible to all cameras within the 1st glide to the instant of breakout, where the swimmer's head broke the surface of the water or their arms were at their greatest separation. The speed reel data were also extracted for this specific time frame.

As different sampling frequencies were used to collect video and speed reel data (50 Hz and 250 Hz respectively), the video-derived data were converted via interpolation, within SIMI Motion, from 50 Hz to 250 Hz and exported to a text file. The video data were interpolated to 250 Hz to maintain the high sampling rate of the speed reel data. Raw speed reel data were imported into SIMI Motion to apply a low pass 2nd order Butterworth filter with a cut off frequency of 7 Hz, to remove high frequency noise, and then exported to a text file.

Synchronisation between data collection methods was completed through the manual identification of an LED located on top of the speed reel via an above water camera. The LED was automatically triggered once the speed reel began data collection. An additional LED was visible above and below the surface of the water to align the underwater cameras to the speed reel LED. The video and speed reel were synchronised by aligning the time point the LED was first visible. CoM speed was used in this analysis due speed reel measuring the overall speed of the swimmer and not giving horizontal or vertical components. Therefore, for a more accurate comparison of speed was used.

No comparative data were available from push off (0.0 s) to the initiation of the fly kick preparation phase as the full body of the swimmers was not visible by all cameras.

5.2.1 Statistical Analysis

The normality and homoscedasticity assumptions were checked respectively with Sharipo Wilks and Levene's tests. The speed-time histories of the following three identified methods were compared: 1) mid-hip (3D video); 2) CoM (3D video); 3) lower back (speed reel). A preliminary analysis of the difference between speed reel and CoM speed and speed reel and mid-hip speed was completed by calculating the root mean square error (RMSE) between each pair of data sets to assess the goodness of fit. Instances of maximum differences between the three data sets were also noted.

Root mean squared error (RMSE) were used as measures of the magnitude of the difference between different methods of speed data collection. Using methods described by Bland-Altman (1985), Bland-Altman plots and limits of agreement (LOA) between speed reel versus 3D CoM data and speed reel and mid-hip were performed. Proportional bias was determined by the identification of the slope of the least squares regression line of differences on averages differed significantly from 0 ($p<.05$) (Ludbrook, 2010). Additionally, the maximum difference found throughout the speed-time curve was identified.

Statistics were performed on data from a wall push and calculated from the initiation of the fly kick preparation phase to breakout and in addition a separate analysis was completed utilising solely the 2nd glide phase, from the peak speed prior to 2nd glide phase to initiation of Arm recovery to compare the full BUP and isolating glide 2.

5.2.2 Definitions of variables

Glide 1 Minimum speed ($m \cdot s^{-1}$) - Minimum CoM speed identified within Glide 1

Fly kick Minimum speed ($m \cdot s^{-1}$) - Minimum CoM speed identified within Fly kick

Fly kick Maximum speed ($m \cdot s^{-1}$) - Maximum CoM speed identified within Fly kick

Pull down Maximum speed ($m \cdot s^{-1}$) - Maximum CoM speed identified within Pull down

Glide 2 and Arm and leg recovery Minimum speed ($m \cdot s^{-1}$) - Minimum CoM speed identified within Glide 2 and Arm and leg recovery

Kick Maximum speed ($m \cdot s^{-1}$) - Maximum CoM speed identified within kick

5.3 Results

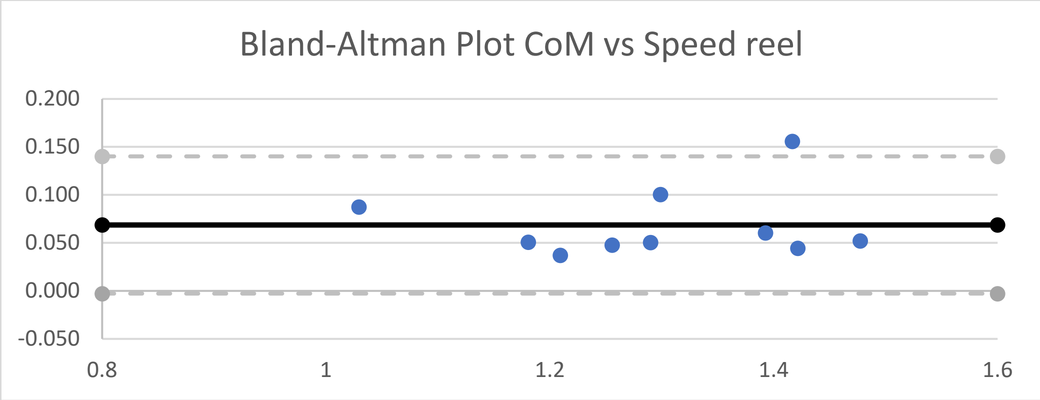


Figure 5.1: Bland–Altman plot for agreement analysis of CoM and speed reel (n = 10). Limits of Agreement are shown with 95% confidence intervals (as dotted grey lines) and bias (as solid black line).

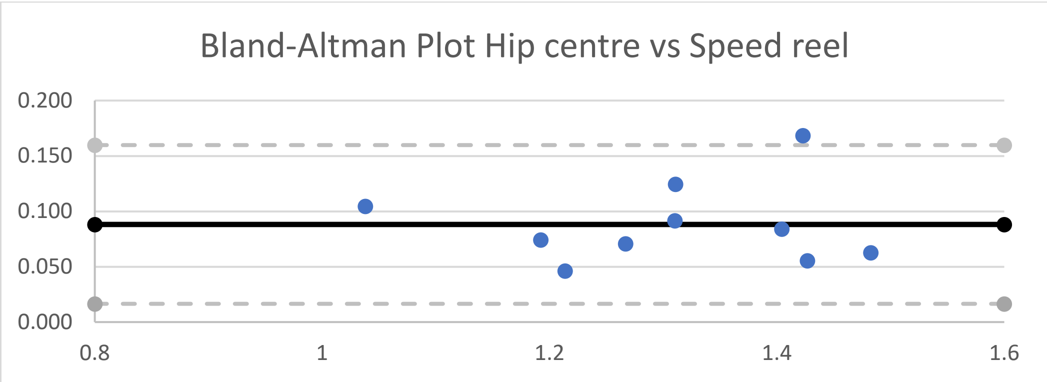


Figure 5.2: Bland–Altman plot for agreement analysis of mid-hip and speed reel (n = 10). Limits of Agreement are shown with 95% confidence intervals (as dotted grey lines) and bias (as solid black line).

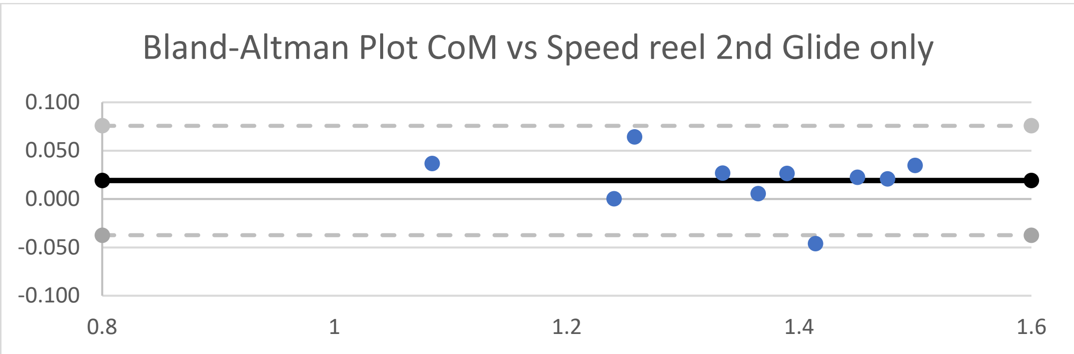


Figure 5.3: Bland–Altman plot for agreement analysis of CoM and speed reel for 2nd glide only (n = 10). Limits of Agreement are shown with 95% confidence intervals (as dotted grey lines) and bias (as solid black line).

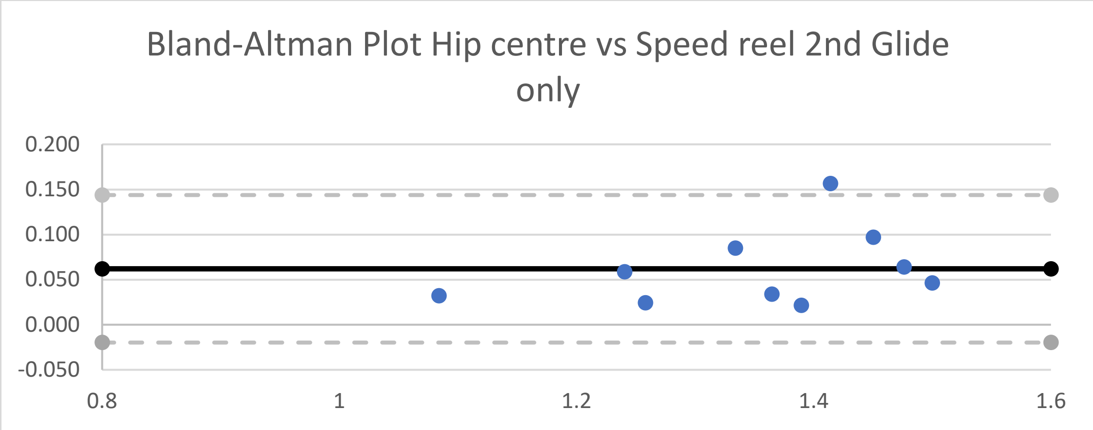


Figure 5.4: Bland–Altman plot for agreement analysis of mid-hip and speed reel for 2nd glide only (n = 10). Limits of Agreement are shown with 95% confidence intervals (as dotted grey lines) and bias (as solid black line).

A proportional bias of 0.069 (95% LoA −0.003 to 0.14) was calculated between CoM and speed reel (Figure 5.1) and a bias of 0.088 (95% LoA 0.016 to 0.16) between mid-hip and speed reel for the entire BUP (5.2).

When isolating the 2nd glide a proportional bias of 0.019 (95% LoA −0.037 to 0.076) was calculated between CoM and speed reel (Figure 5.3) and a bias of 0.062 (95% LoA -0.02 to 0.144) between mid-hip and speed reel (5.4).

Table 5-1: RMSE, maximum difference, standard deviation and range between CoM Speed, Speed Reel and Hip Centre Speed from a wall push off calculated from the initiation of the fly kick preparation phase to the instant of breakout (n=10).

	RMSE ($m \cdot s^{-1}$)	Max Difference ($m \cdot s^{-1}$)
CoM Speed vs Speed Reel	0.22 ± 0.06 (0.14 to 0.31)	-0.48 ± 0.68 (-1.38 to 0.80)
Speed Reel vs Mid-hip Speed	0.23 ± 0.06 (0.16 to 0.33)	-0.85 ± 0.30 (-1.48 to -0.48)

Table 5-2: Mean speed, standard deviation and range for CoM Speed, Speed Reel and Mid-hip Speed from a wall push off calculated from the initiation of the fly kick preparation phase to the instant of breakout (n=10).

	Mean speed ($m \cdot s^{-1}$)	Range ($m \cdot s^{-1}$)
CoM Speed	1.33 ± 0.37	1.07 – 1.50
Mid-hip Speed	1.35 ± 0.43	1.09 – 1.51
Speed Reel	1.26 ± 0.46	1.00 – 1.45

Table 5-3: RMSE, maximum difference, standard deviation and range between CoM Speed, Speed Reel and Mid-hip Speed from a wall push off calculated from the peak speed prior to 2nd glide phase to initiation of Arm recovery (n=10).

	RMSE ($m \cdot s^{-1}$)	Max Difference ($m \cdot s^{-1}$)
CoM Speed vs Speed Reel	0.12 ± 0.04 (0.06 to 0.21)	-0.19 ± 0.32 (-0.68 to 0.42)
Speed Reel vs Mid-hip Speed	0.10 ± 0.07 (0.04 to 0.29)	-0.23 ± 0.21 (-0.68 to 0.15)

Table 5-4: Mean speed, standard deviation and ranges for CoM Speed, Speed Reel and Mid-hip Speed from a wall push off calculated from the peak speed prior to 2nd glide phase to initiation of Arm recovery (n=10).

	Mean speed ($m \cdot s^{-1}$)	Range ($m \cdot s^{-1}$)
CoM Speed	1.40 ± 0.32	1.14 – 1.56
Mid-hip Speed	1.38 ± 0.36	1.10 – 1.52
Speed Reel	1.32 ± 0.34	1.07 – 1.48

A RMSE of 0.22 $m \cdot s^{-1}$ between the speed of CoM and speed reel was observed from the initiation of the fly kick preparation phase to the instant of breakout (Table 5-1) and 0.12 $m \cdot s^{-1}$ for the 2^{nd} glide only (Table 5-3). A RMSE of 0.23 $m \cdot s^{-1}$ between the speed of mid-hip and speed reel was found from the initiation of the fly kick preparation phase to the instant of breakout (Table 5-1) and 0.10 m·s^{-1} for the 2nd glide only (Table 5-3).

Table 5-5: Maximum differences, standard deviation and range between CoM Speed and Speed Reel and Mid-hip Speed and speed reel from a wall push off calculated for glide 1, Fly kick, Pull-down, Glide 2 and arm and leg recovery and Kick (n=10).

Phase	Variable	Speed reel vs CoM speed difference (m·s^{-1}) (n=10)	Speed reel vs Mid-hip speed difference (m·s^{-1}) (n=10)
Glide 1	Minimum speed	-0.34 ± 0.20 (-0.71 to -0.07)	-0.32 ± 0.18 (-0.64 to – 0.06)
Fly kick	Maximum speed	0.48 ± 0.65 (0.03 to 2.27)	0.31 ± 0.70 (-0.10 to 2.27)
	Minimum speed post peak speed	-0.09 ± 0.21 (-0.61 to 0.09)	0.13 ± 0.17 (-0.52 to 0.03)
Pull-down	Maximum speed	0 ± 0.12 (-0.19 to 0.15)	-0.13 ± 0.20 (-0.62 to 0.11)
Glide 2 and arm and leg recovery	Minimum speed	-0.36 ± 0.06 (-0.44 to -0.22)	-0.20 ± 0.09 (-0.31 to 0)
Kick	Maximum speed	0.26 ± 0.11 (0.04 to 0.40)	0.24 ± 0.10 (0.05 to 0.40)

Table 5-5 identifies on average the speed reel underestimates the speed in comparison to CoM and mid-hip speed in the minimum speed post glide 1, minimum speed post fly kick and in the minimum speed post glide 2 and arm and leg recovery. In addition, on average the speed reel overestimates the speed in comparison to CoM and mid-hip speed for the maximum speed in fly kick and kick. The Fly kick maximum speed difference was the largest difference observed for both speed reel vs CoM speed (0.48 m·s^{-1}) and speed reel vs mid-hip speed (0.31 m·s^{-1}).

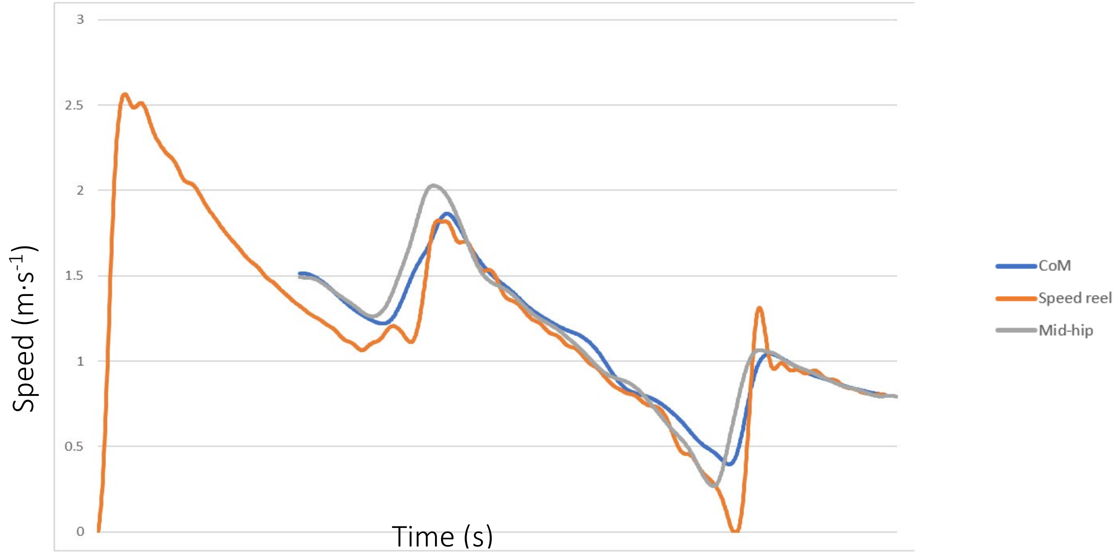


Figure 5.5: Presents comparison speed data for a single swimmer obtained from Speed Reel, CoM from 3D video and Mid-hip location from 3D video (Blue = CoM, Orange = speed reel, Grey – mid hip).

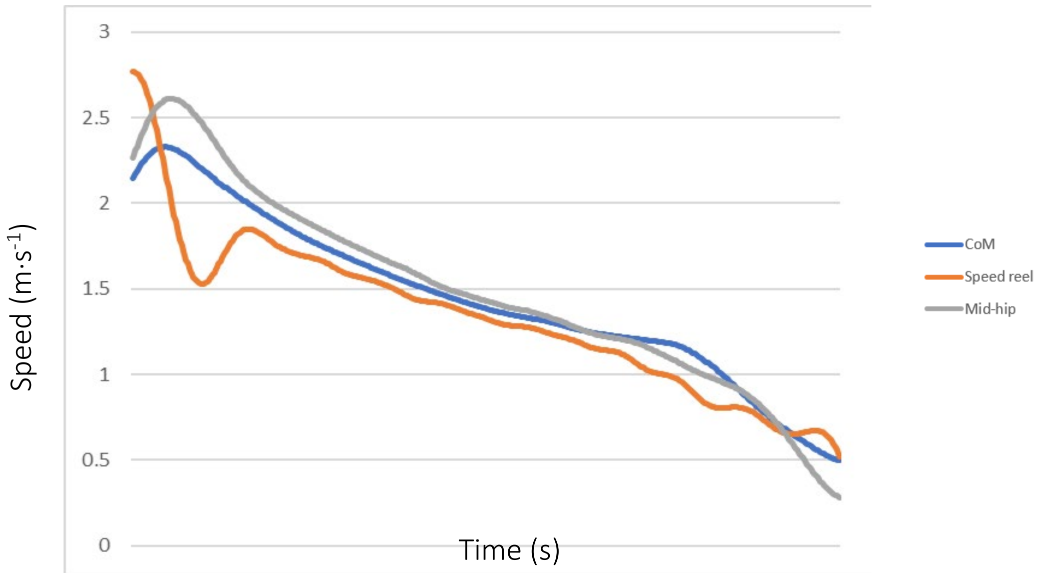


Figure 5.6: Presents comparison speed data for a single swimmer obtained from Speed Reel, CoM from 3D video and Mid-hip location from 3D video for the 2nd glide phase (Blue = CoM, Orange = speed reel, Grey – mid hip).

The greatest difference between the CoM, speed reel and mid-hip speeds occurred during the minimum speed post glide 1 and peak speed of the fly kick with a number of trials also displaying large differences throughout the recovery phase. The overall largest differences observed were -0.48 $m \cdot s^{-1}$ and -0.71 $m \cdot s^{-1}$ between speed reel and CoM speed, and speed reel and hip speed. Max difference of -0.19 and -0.23

m·s^{-1} were found when solely analysing the 2nd glide between the CoM speed and speed reel and mid-hip speed and speed reel, respectively.

5.4 Discussion

The findings of this study identify that CoM, mid-hip and speed reel speed-time curves all display similar patterns, with peak speeds in the traces identified for the propulsive elements of the BUP (dolphin kick, Pull-down and breaststroke kick), and minimal velocities identified corresponding to the resistive phases (first glide, post dolphin kick propulsion and 2nd glide/ Arm + leg recovery). The minimal speed after the dolphin kick was only relevant to the swimmers who demonstrated a continuity technique or glide technique (Seifert *et al*., 2021) in comparison to the superposition technique where an overlap is present between the propulsive dolphin kick and Pull-down resulting in a continuation of speed.

Despite this comparable pattern, differences between CoM and speed reel and mid-hip and speed reel speed curves were observed. Maximum differences between the CoM and speed reel and mid-hip and speed reel were observed during the peak speed of the Fly kick, just prior to peak breaststroke kick speed and at the minimum speed during Glide 2 and Arm + leg recovery, when the arms are around 90° of recovery and just prior to leg propulsion (kick). This highlights that in comparison to CoM speed, speed reel over-estimates peak speeds and under-estimates speed at minimum speeds. The differences that were present between the CoM and speed reel could have been due to the intersegmental actions of the arms and legs affecting CoM speed with the forward displacement of the upper and lower limbs throughout the arm and leg recovery causing the CoM to decelerate less than the hip (location of speed reel attachment) and the backward movement of the legs during the kick, affecting CoM speed.

When comparing velocity meters and mid-hip velocities in free swimming Feitosa *et al. (*2013) and Barbosa *et al. (*2011) both found comparable results that met minimum criteria, with more than 80% of the Bland-Altman plots being within the 1.96 standard-deviation criteria used as a rule of thumb for technique validation. Therefore, based on the results of this study's LOA and 80% of the Bland-Altman plots being within the 1.96 standard-deviation criteria (i.e., 95% interval confidence), the speed reel was seen as adequate for collecting speed data in place of mid-hip or CoM data (Barbosa *et al*., 2011).

As this study found that the largest differences occurred at peak and minimal speeds, an additional comparison of methods was completed, focusing solely on the 2nd glide phase. By isolating the 2nd glide, this study was able to highlight that smaller differences between measurement methods exist when isolating a glide. These values were lower than those recorded for the entire BUP. Additionally, when isolating the 2nd glide smaller mean bias was found of 0.019. These results highlight that although the speed reel was seen to meet the criteria for collecting speed data in place of mid-hip or CoM data throughout the whole BUP, results show a higher level of compatibility when solely isolating the glide phase. A potential reason that the speed reel was found to be more comparable during glide 2 comparisons could be that within this phase, there are no intersegmental actions occurring that contribute to the CoM speed. Therefore, the mid-hip of the swimmer and the fixed point of the speed reel will be travelling at a very similar speed to the CoM. Practically, this showed that the speed reel is a valuable tool for comparing BUP speed, and in particular when focusing on glide velocities.

It must be stated that any differences between the three data sets should not be considered as errors (true value – measured value) as each approach could be providing an equally accurate measure of what it is intended to measure. The speed reel is measuring the rotational speed of the wheel and converts it to the linear speed of the cable via the known radius of the wheel ($v = r\,\omega$) throughout the swimmer's progress whereas the mid-hip speed is tracking the speed of a single point on the body. These differ to CoM speed as the CoM is the only method that accounts for the contribution of limbs. Additionally, the speed reel assumes the horizontal direction of swimmer, and does not have the ability to depict all horizontal, vertical and lateral velocities that are occurring. Therefore, although all directional components of the mid-hip and CoM velocities could have been calculated, the speed of the mid-hip and CoM was used as a more appropriate comparison to speed reel.

Although seen as a sufficient method of speed collection, knowing how the Speed Reel output and speed derived from a fixed point (Hip) differ from the CoM speed will provide a better understanding of how to interpret swimmer speeds obtained using these methods. It is recommended that speed reel minimum and maximum speeds should not be reported as a good representation of swimmer speed. However, glide or total BUP mean speed could be used as a good tool to monitor progression throughout technical interventions.

5.5 Conclusion

This study found that although CoM, mid-hip and speed reel speed time curves all display similar patterns, substantial differences exist between the methods. Most notably, the speed reel over- and under-estimated peak and minimal speeds at key points in the breaststroke underwater phase. It was deemed that the speed reel may provide comparable data to video-derived data in the glide phase. Practically, this showed that the speed reel has some value as a tool for evaluating BUP speed but the output should be interpreted with caution. Although any differences between the three data sets should not be considered as errors, knowing how the Speed Reel output and speed derived from a fixed point (Hip) differ from the CoM speed will provide a better understanding of how to interpret swimmer speeds obtained using these methods.

6 Chapter Six: Temporal phase analysis of the breaststroke underwater phase

6.1 Introduction

Breaststroke swimmers are only permitted to complete one arm stroke completely back to the legs, a dolphin kick prior to the first breaststroke kick, one breaststroke kick and begin the second arm pull before surfacing (FINA SW 7.1). Swimmers are also permitted to travel through 15 m before resurfacing. These rules are substantially different to the other strokes. The BUP includes six phases, 1st glide, dolphin kick, Pull-down, 2nd glide, Arm + leg recovery and kick. The three propulsive phases are the dolphin kick, Pull-down and kick, and three predominantly resistive phases are the 1st glide, 2nd glide, Arm + leg recovery (McCabe *et al*., 2022).

Research has found that underwater velocity, distance and time is highly correlated to start and turn performance in breaststroke events, with Cossor and Mason (2001a) reporting that the underwater phase of a breaststroke start had the greatest influence, in comparison to other start metrics, on time to 15 m specifically in the women's 100 m. McCabe *et al.* (2022) identified that elite breaststrokers perform one of three pull-out techniques: the fly-kick first technique (fly-kick is initiated and completed prior to Pull-down); the combined technique (Pull-down is initiated before the fly-kick is complete, consequently an overlap of phases is observed) and the Pull-down first technique (Pull-down is completed prior to fly-kick) when competing in major long course events over a 5-year period. Seifert *et al.* (2021) however, identified three slightly differing techniques. When analysing short course time trials of 14 swimmers, they identified three coordination profiles, namely: "Continuity"; "Glide"; "Superposition". They defined the Continuity profile as the synchronisation of the arm Pull-down beginning as the fly-kick ends, which is similar to the fly-kick first technique of McCabe *et al.* (2022). The Glide profile was defined as the initiation of the arm Pull-down following a glide phase post completion of the fly-kick. This coordination profile was also incorporated within the fly-kick first technique of McCabe *et al.* (2022) due to the lack of underwater video footage and thus inability to identify a distinct glide portion following the fly-kick completion. The combined technique of McCabe *et al.* (2022) and Superposition profile of Seifert *et al.* (2021) are similar in that both identify an overlap of the arm Pull-down and completion of the fly-kick. In addition, McCabe *et al.* (2022) uniquely observed and identified the Pull-down first technique which was not evident within the Seifert *et al*. (2021) study.

McCabe *et al.* (2022) found that across all race distances, the largest number of swimmers completed the combined technique, followed by the fly-kick first technique and then the Pull-down first technique, following both a start and turn. A year-by-year breakdown revealed that the fly-kick first technique is becoming more popular. McCabe *et al*. (2022) results from 2019 agree with Seifert et al. (2021) who identified the continuity profile (fly-kick first technique) as the most popular. Additionally, McCabe *et al.* (2022) identified that differences existed between the technique utilised by some elite swimmers for their starts and turns. Skill level, gender and whether competing in short course or long course competitions may be contributing factors that influence the style of underwater technique utilised which requires further investigation.

In addition to coordination profiles, Olstad *et al.* (2021) further analysed the arm–leg coordination/timing differences that exist between the start in 50, 100 and 200 m breaststroke events, revealing differences between the 1st and 2nd glide phase and consequently total underwater glide. However, no difference between the events were found for arm–leg coordination and timing of the dolphin kick. They concluded that swimmers did not change the complex inter-limb coordination between the competitive events, but only modified the least complex movement to control (gliding) to adapt to the swimming speed of the respective events.

Although McCabe *et al.* (2022) and Seifert *et al.* (2021) have identified underwater coordination profiles for elite swimmers and Olstad *et al.* (2021) has identified coordination/timing differences between race distances for elite swimmers. Gonjo and Olstad (2021) is the only study to examine the kinematics of the pull-out in elite and sub-elite swimmers. This however was based on the velocity profiles throughout breaststroke races and not the time spent in individual phases of the underwater pull out.

Temporal phase analysis research has been collected on the free swimming phase of breaststroke, showing that at a slower pace e.g., 200 m Breaststroke, swimmers utilise a higher time gap between arm and leg propulsion, that is to say, a longer glide between their propulsive actions. Elite breaststrokers increase their swimming speeds by minimising the intra-cyclic glide, producing complete continuity or overlapping propulsive arm-leg actions (Chollet *et al*., 2004; Seifert and Chollet., 2008; Strzala *et al*., 2013) Additionally, when comparing swimmers of differing skill level, Leblanc *et al*. (2007) found that elite swimmers spent more time overall in propulsive actions than non-elite (Elite: 47.1% vs Non-elite: 41.8%) and had more continuous propulsion because of reduced lag times within their stroke cycle. Information such as this is key to helping coaches and support staff when looking to improve technique and guide skill development (Strzala *et al*., 2013). The importance of this research in free (surface) swimming phase of breaststroke highlights that learning could be made from the temporal phase analysis of the breaststroke underwater phase that could be highly informative to coaches and should be researched to gain a greater knowledge of the temporal characteristics of elite breaststrokers (Oxford *et al*., 2016).

Only a few comparisons between elite and sub-elite breaststrokers performing the BUP have been completed. The most researched phases of the BUP are the 1st and 2nd glides as the ability to maintain a low resistance streamline position in both 1st and 2nd gliding phases is key to minimising the loss of horizontal velocity (Breed and Young, 2003). Vilas-Boas *et al.* (2010) also demonstrated that the drag was lower in the 1st glide than in the 2nd. They attributed this finding to a reduced drag coefficient and reduced frontal area shown to the water due to the arms extended above the head in the 1st glide. Their practical advice for coaches and swimmers was to not only focus on the propulsive elements of the BUP, but to increase the time spent in the 1st glide and reduce the time spent in the 2nd glide, as well as stressing the importance of body position control throughout both glides, especially during the more resistive 2nd glide.

During Arm recovery, swimmers must decide when to initiate their Leg recovery from a streamline position into a breaststroke kick position, ready for the propulsive kick phase of the BUP. Arm + leg recovery is a highly resistive phase and involves an increase in an already high drag force acting on the body in the 2nd glide (Seifert *et al*., 2007). It has been identified that both international and national level swimmers display a negative superposition coordination in this phase, highlighting that swimmers overlap the Arm + leg recovery to minimise the inevitable increase in drag and maintain a high velocity throughout the BUP (Seifert *et al.*, 2007).

Few studies have evaluated the ideal placement of the dolphin kick within the BUP. McCabe, Mason and Fowlie (2012) found that the timing of the dolphin kick placement does not appear to influence the effectiveness of the underwater phase following a breaststroke start or turn. In contrast, Hayashi, Homma and Luo (2015) found that when looked at in relation to the Pull-down, there is a more ideal placement of the dolphin kick in comparison to others, with the dolphin kick being completed approximately 0.4 seconds faster than Pull-down initiation.

Although McCabe, Mason and Fowlie (2012) found that dolphin kick placement does not appear to influence the effectiveness of the underwater phase, participants in their study did travel 0.30 m ($p<.01$) further underwater when using the early dolphin kick variation (11.88 ± 0.86, 8.49 ± 0.85 m) than the late dolphin kick variation (11.57 ± 0.88, 8.19 ± 0.80 m) for starts and turns respectively.

Although some temporal analysis research for the BUP has been completed, to date, no temporal analysis of the BUP has been completed to a level as in-depth as in this study or with the level of World Class swimmers included in the participant group. Additionally, no temporal analysis comparison of the BUP between a start and a wall push-off has been completed.

The aims of this study are to:

1) examine whether BUP timings differ following a wall push compared to a dive start;

2) identify differences between the BUP timing profiles (temporal characteristics) of elite breaststroke specialists and sub-elite swimmers.

6.2 Methods

For the details of the equipment used, data collection, specifics surrounding the calibration of equipment, experimental protocol and data processing refer to Chapter 4: General methods section (p.55).

6.2.1 Definition of key points and phases

Six identified time points for arm actions (A to E) and seven identified time points for legs action (1 to 9) were defined as shown in Figure 6.1. The phases were identified qualitatively utilising two of the eight camera views.

A) *Start of Pull-down* - beginning of hand separation breaking the streamline position

B) *End of Pull-down* - end of backward movement of hands finishing at the hips

C) *Start of Arm recovery* - when the hands start their forward movement relative to the body

D) *End of Arm recovery* - when the elbows are fully extended

E) *1st stroke* – start of first continuous lateral movement of the hands

1) *Upper body dolphin kick preparation* first upper body movement deviating from a streamline position

2) *Lower body dolphin kick preparation* – first upward movement of the feet

3) *Start of dolphin kick down beat* – feet at their highest position in the water

4) *End of dolphin kick down beat* – feet at their deepest position in water

5) *End of dolphin kick upbeat* – lower legs return to horizontal position

6) *Start of Leg recovery* – first upward movement of the heel

7) *End of Leg recovery* – knees in their most flexed position

8) *Start of leg propulsion* – first backward movement of feet move following maximum knee flexion

9) *End of kick* - when the feet complete their inward movement.

Based on the identified points above, the following phases were defined:

a) *1st glide* – between toe immersion/toes leaving the wall and beginning of hand separation breaking the streamline position/ start of dolphin kick preparation phase to the first upper body movement deviating from a streamline position

b) *Upper body dolphin kick preparation phase* – Upper body dolphin kick preparation to start of lower body dolphin kick preparation

c) *Lower body dolphin kick preparation phase* – start of lower body dolphin kick preparation to the start of dolphin kick down beat

d) *Dolphin kick down beat* – start of dolphin kick down beat to the end of dolphin kick down beat

e) *Dolphin kick up beat* - End of dolphin kick down beat to end of dolphin kick upbeat

f) *Pull-down* - start of Pull-down to end of Pull-down

g) 2^{nd} *Glide* – end of Pull-down to start of Arm recovery

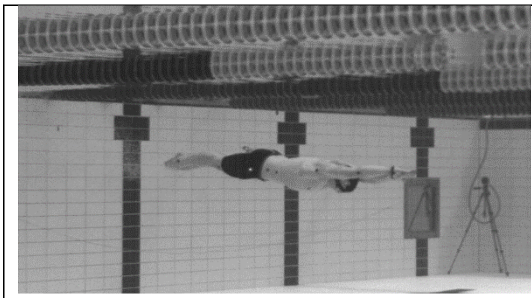
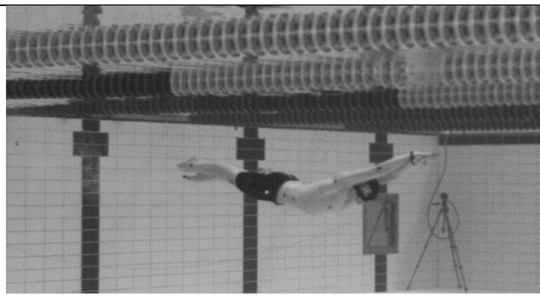
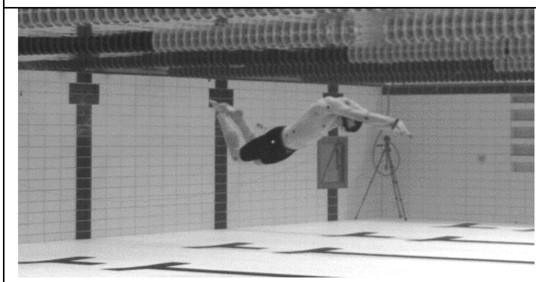
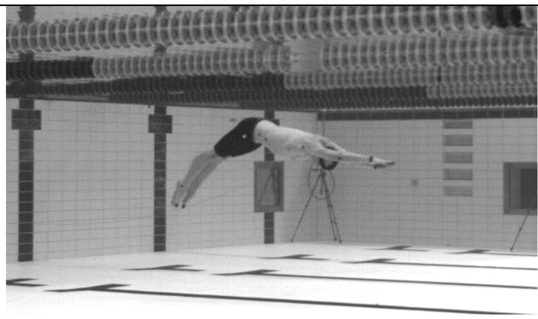
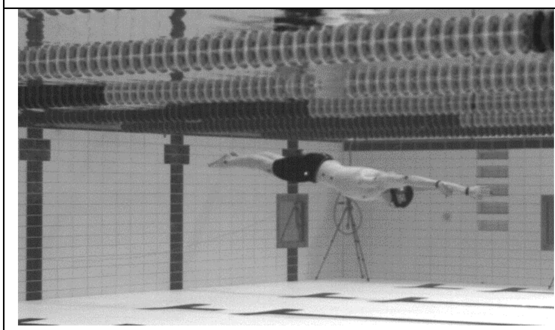
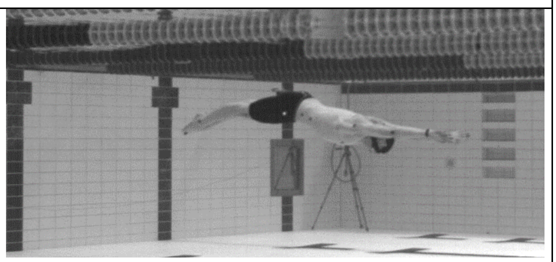
h) *Arm recovery* – start of Arm recovery to end of Arm recovery

i) *Leg recovery* – start of Leg recovery to end of Leg recovery

j) Arm + leg recovery - start of Arm/Leg recovery to end of Arm/Leg recovery

k) *Kick* – Start of leg propulsion to end of kick

l) Arm to leg recovery – difference between the start of the arm recovery and leg recovery

	
1) Start of upper body dolphin kick preparation phase	2) Start of lower body dolphin kick preparation phase
	
3) Start of dolphin kick down beat	4) End of dolphin kick down beat
	
5) End of dolphin kick upbeat	A) Start of Pull-down

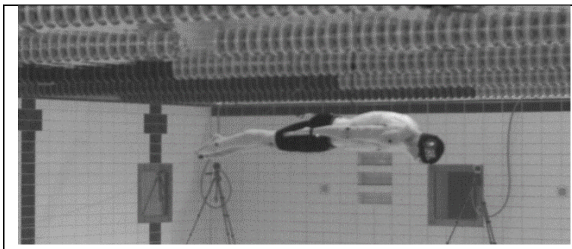
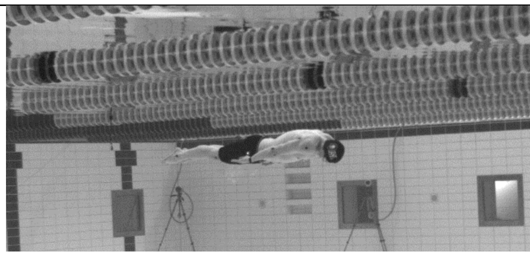
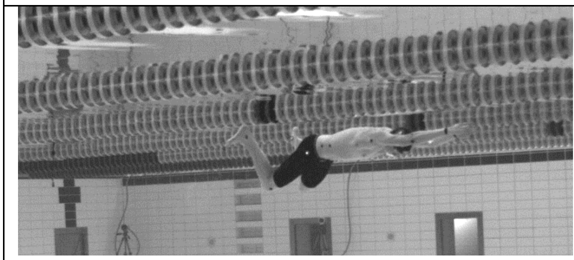
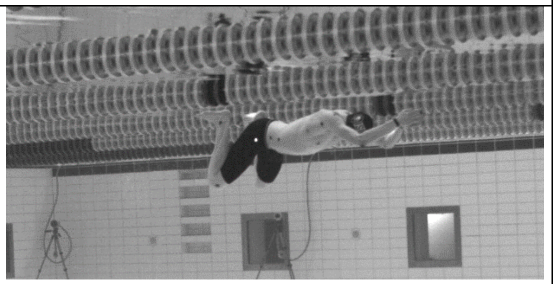
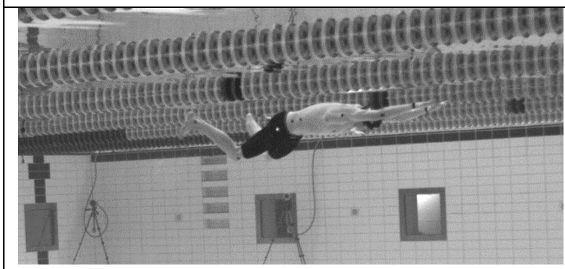
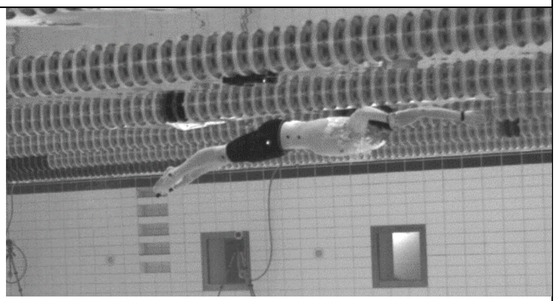
	
B) End of Pull-down	6) Start of Leg recovery C) Start of Arm recovery
	
D) End of Arm recovery	7) End of Leg recovery 8) Start of leg propulsion
	
E) 1st stroke	9) End of kick

Figure 6.1: A) Identification of key movement positions during the BUP with respect to the arm actions (A to E) and leg actions (1 to 9)

6.2.2 Statistical Analysis

The normality and homoscedasticity assumptions were checked respectively with Sharipo Wilks and Levene's tests. Descriptive statistics of means and standard deviations were calculated for all variables.

The mean duration of each phase of the BUP was calculated. Additionally, phase durations were expressed as a percentage of the duration of the complete underwater section. Shapiro–Wilk test found data both did not and did meet the required assumptions therefore Spearman rank correlation coefficients and Pearson correlation coefficients were calculated, respectively, to establish the strength of association between 10 m time and the absolute and relative phase durations for the separated and overlap technique. Specifically, Spearman rank correlations were completed for Glide 1 and 10 m time for the separated technique and for Glide 1 and 10 m time and Fly kick prep for the overlap technique. Correlations were considered significant if $P < .05$. A correlation was considered significant if $P < .05$. Correlations were defined as follows: weak, <.4; moderate, .4 – .6; or strong, >.6 (Mukaka, 2012).

Separate MANOVA's were used to identify differences between phase durations of: 1) the separated versus overlap technique; 2) elite versus sub-elite samples (skill level); 3) dive entry versus wall push-off. Effect sizes were calculated using partial eta squared. Pairwise comparisons were then used to identify further significant differences. In this study, $P < .05$ was considered significant.

The separated technique is defined when the Fly kick is initiated and completed prior to Pull-down, with the overlap technique defined by the Pull-down being initiated before the fly-kick is complete, consequently an overlap of phases is observed.

6.3 Results

When grouped based on skill level, irrespective of technique used, it was found that there was no significant effect found on skill level for duration of the phases or percentage time spent in phases ($F(13, 6) = 1.9$, $p = .22$; Wilk's lambda = .2, partial eta squared = 0.8; $F(13, 6) = 2.09$, $p = .19$; Wilk's lambda = .18, partial eta squared = 0.82 respectively). This shows that when techniques are combined, differences between elite and sub-elite BUP swimmers are not significant. However, when technique was divided in to separated and overlap technique, a significant difference in the Fly kick preparation phase and kick phase were identified, with the separated technique spending 0.1 s longer in the Fly kick preparation phase. This highlighted that potential differences between elite and sub-elite samples could have been masked due to differences in technique and not between the elite and sub-elite samples. Consequently, for the remainder of the analysis, the effect of skill level was statistically analysed using a MANOVA on the separate technique and only descriptive statistics were provided for the overlap technique due to limited numbers.

Table 6-1: Mean time spent in phases and MANOVA to identify the effect of technique on duration in the sub phases

Phase	Separate (s)	Overlap (s)	p
Time 10m	5.68	6.00	.34
Glide 1	1.12	1.38	.06
Fly kick prep	0.15	0.05	.005**
Fly kick recovery	0.34	0.31	.32
Fly kick downbeat	0.26	0.23	.08
Fly kick upbeat	0.27	0.28	.83
Full fly kick	1.02	0.87	.08
Pull-down	0.78	0.77	.88
Glide 2	0.75	0.91	.30
Arm recovery	1.06	1.02	.60
Leg recovery	0.64	0.67	.45
Arm and leg recovery	1.06	1.02	.60
Kick	0.44	0.50	.03*
Glide into 1st stroke	0.01	0.22	.09
Arm to Leg recovery	0.30	0.18	.34

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

For further statistical analysis, the participant sample was divided into the separate and overlap technique as although no significant effect was found on technique for duration of the phases or percentage time spent in phases (F(13, 6) = 3.38, p = .07; Wilk's lambda = .12, partial eta squared = .88, significant differences were noted specifically for the Fly kick preparation phase (p< .01) and kick (r= -.58, p= .03) (Table 6-1).

Table 6-2: Correlation Coefficients between 10 m time and time spent in all sub phases of BUP for the separated technique.

Phase	Correlation Coefficient	p
Glide 1	-.15	.63
Fly kick prep	-.64*	.02
Fly kick recovery	-.08	.81
Fly kick downbeat	.11	.73
Fly kick upbeat	-.14	.68
Full fly kick	-.39	.19
Pull-down	.03	.91
Glide 2	.03	.93
Arm recovery	-.23	.45
Leg recovery	-.02	.95
Arm and leg recovery	-.23	.45
Kick	.81**	<.001
Glide into 1st stroke	-.03	.91
Arm to Leg recovery	-.41	.16

*. Correlation is significant at the .05 level (2-tailed).

**. Correlation is significant at the .01 level (2-tailed).

Table 6-2 shows that for the separated technique, time spent in the Fly kick preparation has a moderate negative correlation to 10 m time (r= -.64, p= .02) with time spent in kick have a strong positive correlation to 10 m time (r= .81, p< .01). No association was found between 10 m time and all other variables.

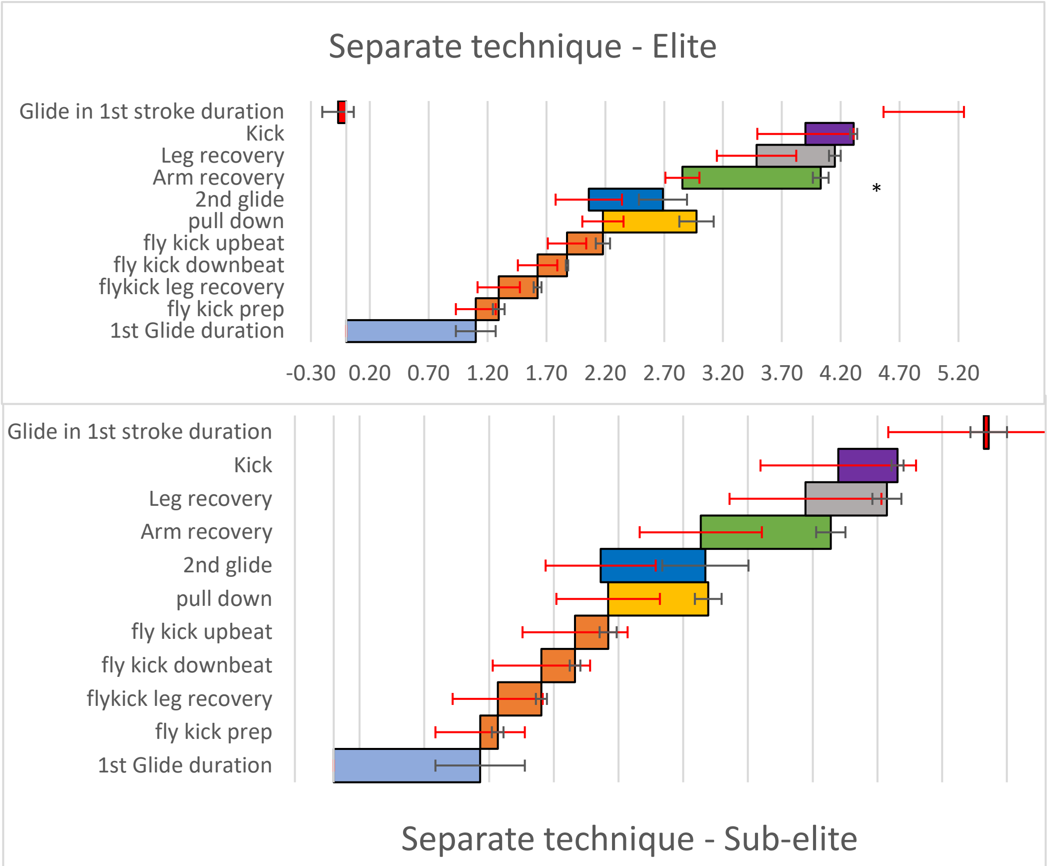
Table 6-3: Correlation Coefficients between 10m time and time spent in all sub phases of BUP for the overlap technique

Event (m)	Correlation Coefficient	p
Glide 1	-.47	.29
Fly kick prep	.13	.78
Fly kick recovery	-.32	.49
Fly kick downbeat	.14	.76
Fly kick upbeat	-.73	.06
Full fly kick	-.53	.22
Pull-down	.56	.19
Glide 2	.14	.76
Arm recovery	.65	.12
Leg recovery	.23	.62
Arm and leg recovery	.65	.13
Kick	.04	.12
Glide into 1st stroke	.78*	.04
Arm to Leg recovery	.58	.17

*. Correlation is significant at the .05 level (2-tailed).

**. Correlation is significant at the .01 level (2-tailed).

Table 6-3 shows that for the overlap technique, time spent in glide into 1st stroke being found to have a strong positive correlation to 10 m time (r= .78, p= .04). No association was found between 10 m time and all other variables.



*. Correlation is significant at the .05 level (2-tailed).

Figure 6.2: Mean, range and standard deviations for start and duration of BUP phases for the separated technique elite and sub-elite samples. The length of the box denotes mean duration of time spent in each BUP phase; the red error bar denotes the standard deviation of start time of the phase; the black error bar denotes the standard deviation of duration of the phase (Appendix 3: Table A). MANOVA was used to identify the effect of skill level on duration in the sub phases.

6.3.1 Phase timings - separated

There was no significant effect found on skill level for duration of the phases or percentage time spent in phases, F(11, 1) = 2.28, p = 48; Wilk's lambda = 0.04, partial eta squared = .962. A further pairwise analysis demonstrated a significant difference between elite and sub-elite swimmers in the duration of the Arm recovery (*p*= .04), Arm + leg recovery (*p*= .04) and arm to Leg recovery (*p*= .01). With elite swimmers spending .21s more time in the Arm recovery and .19s longer in the time spent between the Arm + leg recovery occurring (Appendix 3: Table A).

Table 6-4: Descriptive statistics including mean, range and standard deviations for percentage of time spent in the BUP sub phase for Sub-elite and Elite separated technique (n=11, 4). MANOVA was used to identify the effect of skill level on percentage of time spent in the BUP sub phase for the separated technique.

Phase	Performance Level	N	% Spent in phase ± Std. Deviation	Minimum and maximum % Spent in phase	Sig.
1st Glide	Elite	4	0.22 ± 0.03	(0.19 - 0.27)	
	Sub-elite	11	0.22 ± 0.04	(0.18 - 0.29)	.97
Fly kick preparation	Elite	4	0.04 ± 0.01	(0.02 - 0.05)	
	Sub-elite	11	0.03 ± 0.01	(0.01 - 0.05)	.11
Fly kick recovery	Elite	4	0.07 ± 0.01	(0.06 - 0.07)	
	Sub-elite	11	0.07 ± 0.01	(0.06 - 0.08)	.84
Fly kick downbeat	Elite	4	0.05 ± 0.01	(0.04 - 0.05)	
	Sub-elite	11	0.05 ± 0.01	(0.04 - 0.06)	.32
Fly kick upbeat	Elite	4	0.07 ± 0.02	(0.05 - 0.09)	
	Sub-elite	11	0.05 ± 0.02	(0.02 - 0.07)	.05
Full fly kick	Elite	4	0.22 ± 0.03	(0.21 - 0.26)	
	Sub-elite	11	0.20 ± 0.02	(0.17 - 0.23)	.13
Pull-down	Elite	4	0.17 ± 0.05	(0.12 - 0.23)	
	Sub-elite	11	0.16 ± 0.02	(0.13 - 0.20)	.61
2nd Glide	Elite	4	0.13 ± 0.04	(0.08 - 0.16)	
	Sub-elite	11	0.17 ± 0.06	(0.09 - 0.24)	.27
Arm recovery	Elite	4	0.24 ± 0.02	(0.22 - 0.27)	
	Sub-elite	11	0.19 ± 0.02	(0.15 - 0.22)	.005*
Leg recovery	Elite	4	0.14 ± 0.02	(0.12 - 0.16)	
	Sub-elite	11	0.13 ± 0.02	(0.09 - 0.15)	.46
Kick	Elite	4	0.08 ± 0.01	(0.07 - 0.10)	
	Sub-elite	11	0.09 ± 0.01	(0.07 - 0.12)	.26
Glide in 1st stroke	Elite	4	-0.02 ± 0.03	(-0.06 - 0.01)	
	Sub-elite	11	0.01 ± 0.03	(-0.04 - 0.04)	.23

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

6.3.2 Phase percentage - Separated

There was no significant effect found on skill level for the percentage time spent in phases, $F(11, 1) = 2.17$, $p = .48$; Wilk's lambda = 0.04, partial eta squared = .96. A further pairwise analysis demonstrated a significant difference between elite and sub-elite swimmers being observed in the percentage of total time in Arm recovery ($p < .01$). With elite breaststroke swimmers spending 5% longer in Arm recovery (Table 6-4).

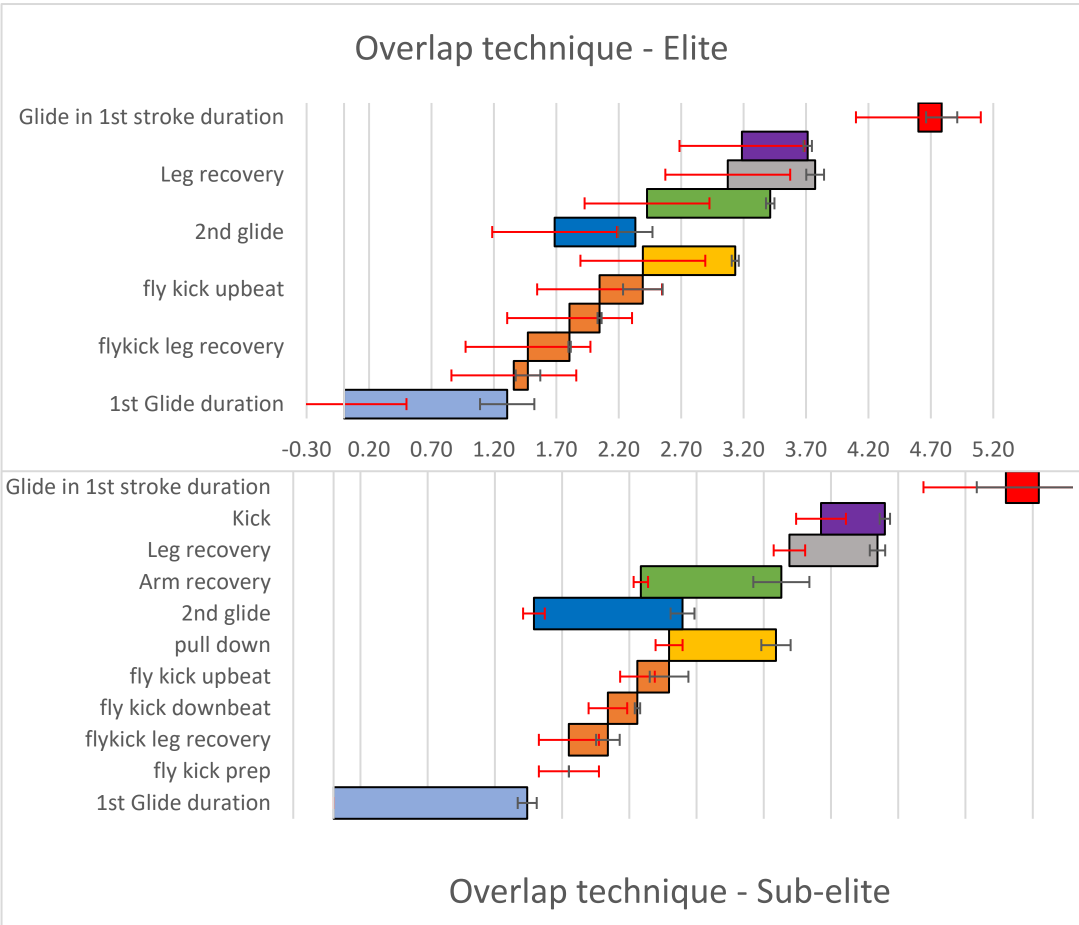


Figure 6.3: Mean, range and standard deviations for start and duration of BUP phases for the overlap technique elite and sub-elite samples. The length of the box denotes mean duration of time spent in each BUP phase; the red error bar denotes the standard deviation of start time of the phase; the black error bar denotes the standard deviation of duration of the phase (Appendix 3: Table B).

Table 6-5: Descriptive statistics including mean, range and standard deviations for percentage of time spent in the BUP sub phase for Sub-elite and Elite overlap technique (n=3, 3)

Phase	Performance Level	N	% Spent in phase ± Std. Deviation	Range of % Spent in phase
1st Glide	Elite	3	0.29 ± 0.08	0.23 - 0.32
	Sub-elite	3	0.29 ± 0.04	0.23 - 0.32
Fly kick preparation	Elite	3	0.02 ± 0.03	0.00 - 0.05
	Sub-elite	3	0.01 ± 0.01	0.00 - 0.02
Fly kick recovery	Elite	3	0.07 ± 0.01	0.07 - 0.08
	Sub-elite	3	0.06 ± 0.03	0.04 - 0.10
Fly kick downbeat	Elite	3	0.05 ± 0.00	0.05 - 0.05
	Sub-elite	3	0.05 ± 0.01	0.03 - 0.06
Fly kick upbeat	Elite	3	0.08 ± 0.05	0.04 - 0.13
	Sub-elite	3	0.04 ± 0.03	0.01 - 0.08
Full fly kick	Elite	3	0.23 ± 0.04	0.21 - 0.27
	Sub-elite	3	0.16 ± 0.07	0.09 - 0.26
Pull-down	Elite	3	0.16 ± 0.01	0.15 - 0.17
	Sub-elite	3	0.16 ± 0.02	0.14 - 0.17
2nd Glide	Elite	3	0.14 ± 0.04	0.11 - 0.18
	Sub-elite	3	0.22 ± 0.06	0.14 - 0.26
Arm recovery	Elite	3	0.22 ± 0.02	0.20 - 0.24
	Sub-elite	3	0.21 ± 0.03	0.19 - 0.25
Leg recovery	Elite	3	0.16 ± 0.03	0.13 - 0.18
	Sub-elite	3	0.13 ± 0.02	0.10 - 0.15
Kick	Elite	3	0.11 ± 0.01	0.11 - 0.12
	Sub-elite	3	0.10 ± 0.01	0.08 - 0.11
Glide in 1st stroke	Elite	3	0.04 ± 0.04	0.00 - 0.07
	Sub-elite	3	0.05 ± 0.08	-0.01 - 0.17

6.3.2.1 Phase timings – Overlap

Due to limited participants who completed the overlap technique, statistical analysis could not be performed. Descriptive statistics, however, show that the largest differences between elite and sub-elite swimmers completing the overlap technique occur during glide 1, Fly kick upbeat, Pull-down and Arm recovery with elite swimmers spending 0.11 seconds less time in glide 1, 0.14 s longer in the Fly kick upbeat, 0.55 s less in the Pull-down and 0.12 s longer in the Arm recovery (Appendix 3: Table B)

6.3.2.2 Phase percentage - Overlap

Descriptive statistics show that the largest differences between elite and sub-elite swimmers completing the overlap technique occur during Fly kick upbeat, 2nd glide and kick with elite swimmers spending 8% less time in the 2nd glide phase (Table 6-5).

6.3.3 Elite verse Sub-elite

Within the elite sample in this study, 4 out of 6 swimmers completed the fly kick first technique. With 2 out of 6 elite completing the overlap. Within in the sub-elite sample 11 out of 14 swimmers completed fly kick first technique. With 3 out of 14 elite completing the overlap. When combined no significant differences were found, however, when broken down into technique, significant differences were found.

Table 6-6: Descriptive statistics (mean, range, standard deviation) for the swimmers' time and percentage time spent in each phase of the BUP for the start and wall push-off. MANOVA was used to identify the effect of start or push off on duration of time and percentage of time spent in the BUP sub phase.

	Duration (s)			Percentage (%)		
Phase	Start	Push	p	Start	Push	p
Glide 1	1.15	1.14	.99	0.26	0.24	.66
Fly kick prep	0.18	0.13	.27	0.04	0.03	.14
Fly kick recovery	0.30	0.34	.04*	0.07	0.07	.4
Fly kick downbeat	0.22	0.25	.11	0.05	0.05	.75
Fly kick upbeat	0.31	0.30	.91	0.07	0.06	.58
Full fly kick	1.00	1.02	.78	0.23	0.22	.34
Pull-down	0.75	0.74	.77	0.17	0.16	.27
Glide 2	0.62	0.73	.43	0.14	0.15	.7
Arm recovery	0.92	0.98	.30	0.21	0.21	.81
Leg recovery	0.63	0.63	.94	0.15	0.14	.57
Kick	0.41	0.45	.41	0.09	0.10	.86
Glide into 1st stroke	-0.05	0.03	.21	-0.01	0.003	.28

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

6.3.4 Dive entry verses wall push-off

6.3.4.1 Phase timings

There was no significant effect found on skill level for the percentage time spent in phases, F(12, 3) = 1.04, p = .56; Wilk's lambda = 0.2, partial eta squared = .81. However, a further pairwise analysis demonstrated a significant difference between start and pushed being observed in the duration of total time in Fly kick recovery (p= .04).

6.3.4.2 Phase percentage

There was no significant effect found on skill level for the percentage time spent in phases, F(12, 3) = .57, p = .79; Wilk's lambda = 0.31, partial eta squared = .69.

6.4 Discussion

This study found that, based on the elite and sub-elite samples the separated technique was performed by a larger number of swimmers. Fifteen of the 20 swimmers completed the separated technique. This included four of the seven elite sample and 11 of the 14 in the sub-elite sample. This is in line with research completed by Seifert *et al.* (2021) who reported the separated technique to be the most common technique performed by their participants. The current study and that of Seifert *et al.* (2021) were conducted in a training environment with underwater cameras increasing the visibility of key point identification. Contradictory findings are reported by McCabe *et al.* (2022), who presented data obtained in competitions from 2010 to 2019 with a much larger sample size. They found the combination technique to be the most commonly used in Olympic and World Championship finalists. However, when year of competition was considered, it was found that in 2019, more of the sample performed the separated/ fly-kick first technique (61%) over the combined/overlap technique (39%).

6.4.1 Elite versus Sub-elite

Among the BUP sub phases, time spent in the Fly kick preparation phase was the only phase negatively correlated to 10 m time for the separated technique. This study is the first to define a Fly kick preparation phase, as although previous research has suggested efficient fly kickers minimise upper limb movement to encourage the alignment of the upper body in the appropriate direction. It has been hypothesised that swimmers complete this to reduce any movement that is perpendicular to the direction of the segment to decrease the fluid flow separation around the hands (Nakashima, 2009). In theory, this makes sense however in reality this is not always observed, as the upper body movement being observed could not be included in a streamline glide nor the propulsive movement of the fly kick. Therefore, a need for the Fly kick preparation phase to be included in this research was required.

In this study no difference in the duration of time spent in the Fly kick preparation phase was observed between the elite sample and the sub-elite sample. However, a moderate negative correlation for Fly kick preparation phase showed that a longer Fly kick prep phase was associated with a faster 10 m time It could be hypothesised that spending a greater duration in this resistive phase could increase levels of drag and consequently reduce the speed of the swimmer. However, the elite swimmers potentially utilised the time spent in this phase to create greater levels of propulsion in the fly kick down beat and upbeat and consequently had the ability to produce sufficient propulsion within the fly kick down beat and upbeat to counteract the drag acting on the body in the kick preparation phase. Further research in this thesis will quantify the amount of upper body movement present in the BUP.

In research, it has been identified that the breaststroke kick should be performed with a quick whip like motion to provide high propulsion in a short time (Mousavi and Bahadoran, 2011). The results of this study, in part, are in alignment with the above statement as irrespective of performance level, time spent in the breaststroke kick, it was found to have a strong negative correlation to 10 m time, highlighting that faster swimmers spent less time in the kick phase than their slower counterparts. Additionally, within free swimming it has been identified that swimmers spend a longer time accelerating with their arm stroke than with their legs however the legs produce the highest propulsive force within the stroke cycle (Maglischo, 2003). This is due to the legs being significantly stronger than the arms and possessing a greater propelling surface area (Vorontsov and Rumyantsev 2000). Although time spent accelerating was not calculated within this chapter, the time spent in the Pull-down and kick phase of the BUP follow a similar trend with swimmers spending on average 0.32 s longer in the Pull-down of the BUP than the breaststroke kick.

Specifically, for the overlap technique, time spent in the Fly kick upbeat and time spent in glide into 1st stroke being strongly correlated to 10 m time. This differs again to the separated technique, highlighting the differences between techniques and the requirement to analyse the techniques independently of each other.

When the separated technique is broken down into individual phases, the elite sample spent a significantly longer duration and percentage in the Arm recovery. As this phase is highly resistive and increases already high drag forces due to the 2nd glide (Seifert *et al*., 2007), it was hypothesised that elite athletes may spend less time in these phases to minimise the effect of drag on their BUP speed; however, this is not the case. In this study, the elite sample spent on average 0.21 s (5%) longer in the recovery phase than the sub-elite sample.

The results in this study are in agreement concur with Seifert *et al.* (2007) who found that both international and national level swimmers have a negative superposition coordination meaning they overlap their Arm recovery and Leg recovery phases following the 2nd glide to maintain a high mean speed throughout the BUP. However, in this study a significant difference was found in the time between the start of the Arm recovery and the start of the Leg recovery. The elite sample delayed their leg recovery by 0.19 s more than sub-elite group, highlighting less of a negative superposition coordination (Appendix 3: Table A). This delay in leg recovery could be seen to have occurred due to the elite sample spending a longer time in the Arm + leg recovery. However, when the time lag between initiation of the arm and leg recovery is normalised to the duration of the arm-to-Leg recovery phase, a significant difference is still present, illustrating that the elite sample delays the recovery of their legs, reducing the negative superposition coordination. This demonstrates that the amount of time spent in this phase may not contribute to a slower BUP if the legs are in the least resistive (fully extended) position throughout a larger percentage of the Arm recovery.

In the Arm + leg recovery, Seifert *et al.* (2021) found that although the arms started their recovery earlier than the legs, the arm recovery did not finish before the kick initiated, meaning that the legs started their propulsive kicking before the Arm recovery reached full extension. This was not in agreement with the current study as all participants finished their Arm recovery before starting their Kick. However, elite swimmers did display a much smaller time difference between the end of Arm recovery and the start of the kick.

Gonjo and Olstad (2021) defined the pull-out as the point from the end of the 1st glide to first backward motion of the hands into the first swimming stroke (breakout stroke). For this defined time frame, they found no differences between elite and sub-elite samples in the duration of the pull-out phase. This result is contradictory to the current research. It could be hypothesised that the lack of significant differences between elite and sub-elite populations found by Gonjo and Olstad (2021) for the pull-out phase could be due to including all BUP phases (Fly kick, pull-down, 2nd glide, Arm + leg recovery) in their definition of the pull-out phase and therefore masking differences that could exist within the individual sub-phases.

Contradictory to other research, no significant difference was found between elite and sub-elite samples for either 1st or 2nd glide phases of the BUP within this study. Gonjo and Olstad (2021) found that, for the first turn of a men's 100 m short course time trial, elite breaststrokers spent less time in the first glide due to their increased glide velocity, and they still travelled further in the glide than the sub-elite swimmers. This is in line with Veiga, Roig and Gómez-Ruano (2016) who found that elite 100 m swimmers breakout sooner, spending less time underwater than their slower counterparts to maximise forward speed as gliding could be an ineffective method of maintaining a high velocity. However, further results found by Gonjo and Olstad (2021) were in agreement with the current research, as Gonjo and Olstad (2021) did not find supporting evidence of a reduced 1st glide by elite swimmers in comparison to sub-elite swimmers for the dive, 2nd or 3rd turn.

A potential reason for differences found between the current study and Gonjo and Olstad (2021) could be the definition of elite. Gonjo and Olstad (2021) defined their elite swimmers as finalists in a Senior Short Course National Championships and the sub-elite swimmers competed in the same competition however did not make it through to the final. Adopting the criteria used in their study, if a national championship swimmer solely swam in national events they would be classed sub-elite in this current study. However, although Veiga, Roig and Gómez-Ruano's (2016) elite sample was based on World Championship level swimmers (which is similar to the Olympic/World championship level swimmers defined as elite in this study). The research was based on the 2013 World Championships, thus, pre the 2014 rule change, before swimmers were permitted to perform a single dolphin kick at any point prior to the first breaststroke kick, which consequently could have changed how long breaststrokers spend in the BUP.

Although it was previously thought to be beneficial to glide for longer in both glide phase due to elite breaststrokers being found to travel for longer and further out of a turn in all strokes bar freestyle (Veiga *et al.,* 2014). With research finding that elite breaststrokers spend between 9.8 and 30% longer gliding underwater than sub-elite breaststroker's dependent on event (D'Acquisto *et al*., 1998; Seifert *et al*., 2006), more recent research has stated that spending a longer time in the 2nd glide phase may not be as effective as previously suggested due to the high levels of drag acting during this phase (Marinho *et al*., 2011; Seifert *et al*., 2006; Vilas-Boas *et al*., 2010).

6.4.2 Dive entry versus wall push-off

When comparing the BUP from a dive and wall push-off, a significant difference was demonstrated only in the duration spent in the Fly kick recovery phase with a longer duration being found from a wall push-off, no significant differences were identified for any other phase. Additionally, when normalised to percentage of total BUP, no significant differences were observed between start and push. This shows that breaststroke swimmers spend different lengths of time within the Fly kick recovery phase but similar times and percentages of total BUP time in the other phases when completing a start verses a push. This could highlight that, irrelevant of speed, the swimmer coordinates their movement to spend the same duration in each phase. Although the temporal sequencing of the phases has been found to be the very similar following the dive entry and wall push-off, the trajectories of the body and body orientations may differ due to entry angle off a start and angle from the wall following a push. Therefore, other kinematic variables of the sub phases may be completed differently. Further research is required to identify further differences between completing a BUP from a start or wall push-off.

When developing the BUP, breaststroke swimmers can practise the skill as deconstructed phases to make technical improvements however this prevents practice of transition points and the reconstructed skill as a whole is not considered. Therefore, performing the BUP as a whole off both start and turn is essential to develop the adaptability and movement variability of the swimmer, thus preparing them for competition (Hodges and Williams, 2020).

6.5 Conclusion

This study found that the majority of swimmers performed the separated technique; a minority used the overlap technique. Specifically, when focusing on the separated technique the time spent in the Fly kick preparation phase and kick were correlated to 10 m time. When broken down into individual phases, the elite sample spent a significantly longer duration and percentage in the Arm recovery and in the time between the arm to Leg recovery. This identifying that the amount of time spent in these phases may not contribute to a slower BUP as hypothesised if the legs are in the least resistive (straight) position throughout a larger percentage of the Arm recovery. In addition, when comparing the temporal phases analysis of the BUP between starts and pushes a significant difference for fly kick recovery phase was found highlighting the importance of when developing the technique of the BUP; breaststroke swimmers must practice their underwater phases from starts, turns and pushes to enable the swimmers the ability to perform their underwater phase to the best of their ability under a variety of circumstances.

7 Chapter Seven: CoM trajectories and speed profiles of the breaststroke underwater phase

7.1 Introduction

Swimming is characterised by the interaction of propulsive and resistive forces (drag). The aim of the swimmer is to maximise the propulsive forces to overcome the resistive forces (drag) throughout a race. Both maximising propulsion and reducing drag can contribute to the improved performance of a swimmer (Zhan *et al*., 2014). Breaststroke free swimming has been found to have the largest intra-cyclic variations of the horizontal velocity in comparison to other strokes (Barbosa *et al*., 2012). This is due to its bi-modal profile consisting of two peaks in velocity from the propulsive arm and leg actions and the subsequent glide phases (Barbosa *et al*., 2010). Although there is contradictory research into the relationship between intra-cyclic variations and mean swimming velocity in breaststroke swimming (Takagi *et al*., 2004; Leblanc *et al*., 2007; Barbosa *et al.,* 2010; Barbosa *et al.,* 2005; Van Houwelingen *et al.* 2017), all concluded that a swimmer's mechanical work would be lower by reducing intra-cyclic velocity fluctuations, specifically in shorter sprint events.

Minimal research has been conducted into the velocity fluctuations that occur in the breaststroke underwater phase even though it involves a considerable amount of speed fluctuation due to the lack of continuity in the propulsion (Gourgoulis *et al*., 2018). Typically, the swimmer experiences three speed peaks created during the propulsive phases and two velocity minima associated with the glide and recovery phases. The challenge to the swimmer is to adapt timings and technique to increase propulsion when the instantaneous velocity decreases below the mean swimming velocity, and to glide when the instantaneous velocity is above the mean swimming velocity (Seifert *et al*., 2007). The amplitude of intra-cyclic velocity variations and maximum and minimum instantaneous velocities have been identified as a crucial parameter linked to swimming performance (Psycharakis *et al*., 2010) and could inform the development of the BUP.

Seifert *et al. (*2007) state that to positively influence start time and future velocity, breaststroke swimmers must have the ability to correctly organise their underwater phases to gain the best outcome. They must also complete an effective arm-to-leg coordination pattern to increase forward displacement during propulsion, glide and recovery phases enabling a longer underwater phase with minimal velocity loss and less instantaneous velocity fluctuations.

When comparing intra-cyclic velocity variations between strokes or separate samples in swimming, studies regularly identify discrete variables such as mean, maximum and minimum velocities and calculate variation as a percentage of minimum velocity (Takagi *et al*., 2004) or percentage of mean velocity (Psycharakis *et al*., 2010). Whilst these studies have contributed to the understanding of velocity variations within stroke, an additional and potentially more comprehensive method of assessing intra-cyclic velocity variations is to use the index of variation of intra-cyclic velocity (VIV Index) (Rejman, Siemontowski and Siemienski, 2020) or intra-cyclic velocity variation (IVV) through determining the coefficient of variation (Matsuda *et al.,* 2014). These metrics assess intra-cyclic velocity variations by identifying the area between the curve of instantaneous swimming velocity and the mean velocity and divide the result by the distance covered (VIV Index) (Rejman, Siemontowski and Siemienski 2020). Or, alternatively by determining the coefficient of variation of the horizontal velocity, that is, calculating intra-cyclic velocity variation (IVV) by dividing the standard deviation of velocity by the mean velocity and converting to a percentage (Matsuda *et al.,* 2014). This enables researchers to analyse the skill or stroke cycle as a whole and consider all of the velocity fluctuations that occur throughout the skill. IVV is regularly used to quantify velocity fluctuations and infer energy expenditure and inefficiencies within strokes. Positive relationships have been reported between IVV and energy cost in breaststroke (Vilas-Boas, 1996). Due to this positive relationship a large number of studies have calculated IVV within breaststroke free swimming (e.g., Lebalanc *et al.,* 2007; van Houwelingen *et al*., 2017; Takagi *et al*., 2004).

Although Psycharakis *et al.* (2010) identified the amplitude of intra-cyclic velocity variations as a crucial parameter linked to swimming performance, within breaststroke research there are debates surrounding the association between IVV and swimming performance. For example, Takagi *et al. (*2004) reported that faster swimmers showed lower IVV in breaststroke, while Lebalanc *et al. (*2007) reported that elite swimmers showed a higher maximal peak velocity in a stroke cycle, resulting in higher IVV in breaststroke. Thus, these studies suggest that IVV for elite swimmers may or may not be lower than sub-elite swimmers. However, IVV has yet to be applied to the breaststroke underwater phase.

A method of data analysis which has recently grown in popularity within sports biomechanics research is Statistical parametric mapping (SPM). SPM enables researchers to utilise the whole data set and analyse velocity-time curves and other continuous data, without reducing data to discrete measures (Colyer and Salo 2017). An additional benefit of using SPM in elite sport is that an individual's velocity time curves can be identified and analysed without mean group analysis masking the individual properties of elite athletes (Colyer and Salo 2017). This enables elite swimmer's interpretation of the technique and its subsequent success (Barbosa *et al*., 2010b). Within breaststroke the first study to do this was by Gonjo and Olstad (2021) who used SPM to investigate the differences throughout 100 m breaststroke between elite and sub-elite swimmers. They used time-series velocity data to understand how distinct levels of swimmers change their velocity profile throughout breaststroke races, particularly during the underwater phase after the start and turns. They reported that elite swimmers are characterised by higher clean-swimming and 1st glide velocity within the BUP. However, no statistical differences were found for velocities between the samples in the pull-out segment. The pull-out segment in this study was defined as the time from end of 1st glide to the backward hand motion of the hands for the first surface swimming stroke. The study stated that it was unclear why similar pull-out velocity profiles were found between samples. A potential reason for this may have been that both their elite and sub-elite swimmers performed at the same championship level and therefore a large enough difference was not present. An additional reason may have been due to their definition of elite being based on overall race time and not specifically focused on the underwater phase performance.

In the limited studies that have been conducted on the BUP, the participants have been described as international, national, sub-elite and/or elite. The highest performance level of swimmers studied to date were those in the study by Gonjo and Olstad (2021) where the elite participants all had FINA points above 700.

To date, no study of BUP speed profiles has been conducted with World Class swimmers, that is swimmers who have achieved the A qualifying standards set to compete at the international events, which corresponds to ≥ 875 FINA points. Additionally, no study of mass centre trajectories and speed profiles in the BUP has been undertaken on swimmers of any level.

The aims of this study are to:

1) establish if differences exist in the CoM trajectories and speed profiles of elite and sub-elite BUP breaststroke swimmers performing the BUP;

2) determine the relationships between CoM trajectories, speeds and performance in the BUP.

7.2 Method

Data for this study were obtained using the 3D video capture system. For details of the equipment used, calibration procedures, data collection, experimental protocol and data processing, please refer to Chapter 4: General Methods (p.55)

For this study, Centre of Mass horizontal velocity was calculated from the initiation of the fly kick to the instant of breakout, defined as moment the swimmer's head breaks the surface of the water or when their arms reach the widest part of the stroke.

CoM displacement signals were smoothed using a quantic spline. The CoM speed-time series were normalised using linear length normalisation by interpolating the signal to 101 points. The normalised CoM speed-time histories were then divided into elite and sub-elite samples as per defined in the general methods.

7.2.1 Calculation of Dependent Variables

The calibration frame was placed between 2.48 - 2.69 m away from the wall, dependent on data collection session. Thus, all distances in the Y direction were corrected, dependent on calibration frame placement. Therefore, all y distances reported in this study were calculated from the pool wall and not the calibration frame origin.

7.2.2 Definitions of variables

Start of phase velocity ($m \cdot s^{-1}$) – CoM horizontal velocity at the initiation of the phase (phases identified in chapter 6).

End of phase velocity ($m \cdot s^{-1}$) – CoM horizontal velocity at the end of the phase (phases identified in chapter 6).

Minimum velocity of phase ($m \cdot s^{-1}$) – minimum CoM horizontal velocity reached throughout the resistive/glide phases including both glide 1 and 2, preparation/recovery Kick, and Arm + leg recovery (phases identified in chapter 6).

Maximum velocity of phase ($m \cdot s^{-1}$) – maximum CoM horizontal velocity reached throughout each propulsive phase including the Fly kick upbeat, down beat, Pull-down and kick (phases identified in chapter 6).

Distance of minimum velocity (m) – distance identified when minimum CoM horizontal speed reached throughout the resistive/glide phases including both glide 1 and 2, Fly kick preparation/recovery, and Arm + leg recovery (phases identified in chapter 6).

Distance of maximum velocity (m) **–** distance identified when maximum CoM horizontal speed reached throughout each propulsive phase including the Fly kick upbeat, down beat, Pull-down and kick (phases identified in chapter 6).

Mean velocity of phase ($m \cdot s^{-1}$) – mean CoM horizontal velocity throughout the phases (phases identified in chapter 6).

Start of phase distance (m) – CoM horizontal distance at the initiation of the phase (phases identified in chapter 6).

End of phase distance (m) – CoM horizontal distance at the end of the phase (phases identified in chapter 6).

Distanced gained from start to end of phase (m) – Distance travelled from start to end of the phases (phases identified in chapter 6).

Intra-cyclic speed variation (IVV) - was determined by calculating the coefficient of variation of the CoM horizontal velocity between minimum and maximum velocities.

IVV = (standard deviation of horizontal speed / mean horizontal speed) × 100

7.2.3 Statistical Analysis

The normality and homoscedasticity assumptions were checked respectively with Sharipo-Wilks and Levene's tests. Descriptive statistics of means and standard deviations were calculated for speed and distance travelled in each sub phase (in alignment with chapter 6).

Shapiro–Wilk test found data both did not and did meet the required assumptions therefore Spearman rank correlation coefficients and Pearson correlation coefficients were calculated respectively to establish the strength of association between BUP 10 m time and start, end, min/max, and mean velocities and distances. Specifically, Spearman rank correlations were completed for Pulldown end of phase velocity, Glide 2 start of phase velocity, Fly kick downbeat mean velocity, Pulldown start distance and 10 m time for the separated technique and Fly kick prep minimum velocity distance for the overlap technique. When techniques were combined Pulldown start distance was the sole variable where Spearman rank correlations were completed.

A correlation was considered significant if $P < .05$. Correlations were defined as follows: weak, <.4; moderate, .4 – .6; or strong, >.6 (Mukaka, 2012).

MANOVA was used to identify the effect of skill level on all CoM speed profiles for the techniques combined and the separated BUP technique. Effect sizes were calculated using partial eta squared. Pairwise comparisons were then used to identify further significant differences. In this study, a $P < .05$ was considered a significant difference. Only descriptive statistics were obtained for the overlap BUP technique due to a small sample.

In addition, statistical parametric mapping (SPM) was also used to quantitatively identify whether there were differences between samples at a threshold of $p<.05$. An independent test was completed to statistically analyse the IVV with a SPM analysis being completed via a SPM two-tailed nonparametric t-tests was used to compare between elite and sub-elite samples. The SPM analyses were completed using the SPM1D package (version 0.4.3, https://spm1d.org/) on the bespoken MATLAB with $\alpha = .05$.

7.3 Results

7.3.1 CoM horizontal velocity and distance

Table 7-1: Correlation Coefficients between 10m time and start, end, max/min velocity and distance, mean velocity, distance gained and total mean and breakout distance of BUP for both techniques*, the separated and overlap techniques.*

Phase	Variable	Both techniques Velocity	Both techniques Distance	Separated Velocity	Separated Distances	Overlap Velocity	Overlap Distances
BUP	Total mean	-.82**	-	-.84**	-	-.81*	-
	Breakout Distance	-	-.57**	-	-.63*	-	.13
Glide	End of phase	-.50*	-.38	-.48	-.38	-.20	-.78
Fly kick - Prep/recovery	Start of phase	-.56*	-.27	-.53	-.36	-.34	-.30
	End of phase	-.45*	-.47*	-.54*	-.51	-.23	-.70
	Minimum velocity/ distance of minimum velocity	-.67**	-.52*	-.67**	-.50	-.40	-.71
	Mean velocity	-.56*	-	-.55*	-	-.38	-
	Distance Gained	-	-.66**	-	-.63*	-	-.67
Fly kick - down beat	End of phase	-.27	-.44	-.60*	-.47	-.48	-.73
	Maximum velocity/ distance of maximum velocity	-.30	-.40	-.53*	-.45	-.45	-.7
	Mean velocity	-.36	-	-.73**	-	-.38	-
	Distance Gained		-.21	-	-.16	-	-.53
Fly kick - upbeat	End of phase	-.13	-.52*	-.49	-.53*	-.21	-.87*
	Maximum velocity/ distance of maximum velocity	-.22	-.46*	-.58*	-.49	-.51	-.81
	Mean velocity	-.19	-	-.55*	-	-.17	-
	Distance Gained	-	-.43	-	-.35	-	-.96**

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

Table 7-1 shows that when both techniques are combined and when the separated and overlap techniques are considered separately, many of the velocity and distance metrics correlate significantly with 10 m time. With total BUP mean speed being strongly correlated to 10 m time for both techniques and the separated technique (p < .05).

End of glide 1 speed and start of Fly kick preparation speed (r= -.50, p= .03 and r= -.56, p= .01 respectively) were found to have a moderate negative correlation to 10 m time when techniques were combined, however no association was found for the separated technique (Table 7-1). End of Fly kick preparation phase and Fly kick preparation phase mean speed were found to have a moderate negative correlation when both techniques were combined (r= -.45, p= .045 and r= -.56, p= .01 respectively) and for the separated technique (r= -.54, p= .048 and r= -.55, p= .04 respectively). Fly kick preparation phase minimum speed was also found to have a strong negative correlation to 10 m time for both techniques combined and the separated technique (r= -.67, p< .01 and r= -.67, p< .01 respectively) (Table 7-1).

No associations were present for Fly kick downbeat start, end, maximum and mean speeds when techniques were combined however moderate negative correlations were found for Fly kick downbeat end (r= -.60, p= .02), Fly kick downbeat maximum speed (r= -.53, p= .049) and Fly kick downbeat mean speed of the separated technique (r= -.56, p= .04), no association was still found for start of phase speed (Table 7-1).

Similarly, no associations were present for Fly kick upbeat start, end, maximum and mean speeds when techniques were combined, however moderate negative correlations were found for Fly kick upbeat start speed (r= -.60, p= .02), Fly kick upbeat maximum speed (r= -.60, p= .03) and Fly kick upbeat mean speed (r= -.55, p= .04) of the separated technique. No association was found for Fly kick upbeat end of phase speed (Table 7-1).

When both techniques were combined, Fly kick preparation phase distance gained was found to have a strong negative correlated to 10 m time (r= -.66, p< .01). Breakout distance (r= -.57, p< .01), Fly kick preparation phase end of phase (r= -.47, p= .04) and Fly kick preparation minimum velocity distance (r= -.52, p= .02), Fly kick upbeat end of phase (r= -.52, p= .02) and Fly kick upbeat maximum velocity distance were found to have a moderate negative correlation to 10 m time (r= -.46, p= .04) (Table 7-1).

For the separated technique, breakout distance, Fly kick preparation phase distance gained were found to have a strong negative correlation to 10 m time (r= -.63, p= .02 and r= -.63, p= .02 respectively) with Fly kick upbeat end of phase distance having a moderate negative correlation (r= -.55, p= .049). The overlap technique also found Fly kick upbeat end distance and Fly kick upbeat distance gained to have a strong negative correlation to 10 m time (r= -.87, p= .04 and r= -.96, p= .02 respectively) (Table 7-1).

Table 7-2: Correlation Coefficients between 10m time and start, end, max/min velocity and distance, mean velocity, distance gained and total mean and breakout distance of BUP for both techniques, the separated and overlap techniques.

Phase	Variable	Both techniques Velocity	Both techniques Distance	Separated Velocity	Separated Distances	Overlap Velocity	Overlap Distances
Pulldown	Start of phase	-.50*	-.56**	-.58*	-.48	-.14	-.79
	End of phase	-.74**	-.57**	-.68**	-.49	-.73	-.64
	Maximum velocity/ distance of maximum velocity	-.77**	-.57**	-.83*	-.49	-.71	-.67
	Mean velocity	-.81**	-	-.90	-	-.52	-
	Distance Gained	-	-.27	-	-.37	-	.64

*. Correlation is significant at the .05 level (2-tailed).

**. Correlation is significant at the .01 level (2-tailed).

Table 7-3: Correlation Coefficients between 10m time and start, end, max/min velocity and distance, mean velocity, distance gained and total mean and breakout distance of BUP for both techniques, the separated and overlap techniques.

Phase	Variable	Both techniques Velocity	Both techniques Distance	Separated Velocity	Separated Distances	Overlap Velocity	Overlap Distances
Glide 2	Start of phase	-.74**	-.57**	-.74**	-.50	.70	-.64
	End of phase	-.52*	-.55*	-.47	-.49	-.58	-.65
	Minimum velocity/ distance of minimum velocity	-.52*	-.55*	-.47	-.49	-.58	-.65
	Mean velocity	-.70**	-	-.67**	-	-.79	-
	Distance Gained	-	-.08	-	-.16	-	.15

*. Correlation is significant at the .05 level (2-tailed).

**. Correlation is significant at the .01 level (2-tailed).

When both techniques were combined Pull-down start of phase velocity (r= -.50, p= .02), Pull-down end of phase velocity (r= -.74, p< .01), Pull-down mean velocity (r= -.81, p< .01) and Pull-down maximum velocity (r= -.77, p< .01) were found to have a moderate to strong negative correlation to 10 m time (Table 7-2).

Glide 2 start of phase velocity (r= -.74, p< .01), glide 2 end of phase velocity (r= -.52, p= .02), glide 2 mean velocity (r= -.70, p< .01) and glide 2 minimum velocity (r= -.52, p= .02) also showed a moderate to strong negative correlation to 10 m time when techniques were combined (Table 7-3).

Specifically, for the separated technique, Pull-down start of phase velocity (r= -.58, p= .03) was found to have a negative moderate correlation to 10 m time with Pull-down end of phase velocity (r= -.68, p< .01) and Pull-down maximum velocity (r= -.83, p <.01) were found to have a strong negative correlation to 10 m time (Table 7-2).

Glide 2 start of phase velocity (r= -.74, p= .02) and glide 2 mean velocity (r= -.67, p= .01) also showed strong negative correlations for the separate technique (Table 7-3).

Table 7-4: Correlation Coefficients between 10m time and start, end, max/min velocity and distance, mean velocity, distance gained and total mean and breakout distance of BUP for both techniques, the separated and overlap techniques.

Phase	Variable	Both techniques Velocity	Both techniques Distance	Separated Velocity	Separated Distances	Overlap Velocity	Overlap Distances
Arm and leg recovery	Start of phase	-.52*	-.55*	-.47	-.49	-.58	-.65
	End of phase	-.11	-.62**	-.02	-.60*	-.66	-.73
	Minimum velocity/ distance of minimum velocity	-.41	-.62**	-.38	-.61*	-.73	-.69
	Mean velocity	-.65**	-	-.63*	-	-.70	-
	Distance Gained	-	-.41	-	-.55*	-	.31

*. Correlation is significant at the .05 level (2-tailed).

**. Correlation is significant at the .01 level (2-tailed).

Mean velocity of the Arm + leg recovery phase was found to have a strong negative correlation for both techniques combined and the separated technique (r= -

.65, p< .01 and r= -.63, p= .02 respectively), with arm and leg start of phase velocity also showing a strong negative correlation for both techniques combined (r= -.51, p= .02) (Table 7-4).

When both techniques were combined, Arm + leg recovery end of phase distance, Arm + leg recovery minimum velocity distance were found to have a strong negative correlation to 10 m time (r= -.62, p< .01 and r= -.62 p< .01 respectively), with Arm + leg recovery start of phase distance having a moderate negative correlation to 10 m (r= -.55, p= .01) (Table 7-4).

For the separated technique, Arm + leg recovery end of phase distance and Arm + leg recovery minimum velocity distance were found to have a strong negative correlation to 10 m time (r= -.60, p= .02), with Arm + leg recovery distance gained having a moderate negative correlation (r= -.55, p= .04) (Table 7-4).

Table 7-5: Correlation Coefficients between 10m time and start, end, max/min velocity and distance, mean velocity, distance gained and total mean and breakout distance of BUP for both techniques, the separated and overlap techniques.

Phase	Variable	Both techniques Velocity	Both techniques Distance	Separated Velocity	Separated Distances	Overlap Velocity	Overlap Distances
Kick	Start of phase	-.38	-.62**	-.33	-.60*	-.68	-.69
	End of phase	-.60**	-62**	-.50	-.59*	-.93**	-.70
	Maximum velocity/ distance of maximum velocity	-.59**	-.61*	-.53*	-.59*	-.93**	-.69
	Mean velocity	-.45*	-	-.43	-	-.79	-
	Distance Gained	-	.02	-	.04	-	-.48

*. Correlation is significant at the .05 level (2-tailed).

**. Correlation is significant at the .01 level (2-tailed).

For the kick phase, kick maximum velocity was the only correlated variable in the separated technique (r= -.53, p= .049). Kick end of phase velocity (r= -.93, p< .01) and kick maximum velocity were found to have a strong negative correlation to 10 m time for the overlap technique (r= -.93, p< .01). When techniques were combined kick mean velocity was found to have a moderate negative correlation to 10 m time (r= -.45, p= .048) (Table 7-5).

For the separated technique, start of kick distance (r= -.60, p= .03), end of kick distance (r= -.59, p= .03) and maximum kick velocity distance were moderately correlated to 10 m time (r= -.60, p= .03) (Table 7-5).

When both techniques were combined, start of kick distance (r= -.62, p< .01), end of kick distance (r= -.62, p< .01) and maximum kick velocity distance were all found to be strongly correlated to 10 m time (r= -.61, p< .01) (Table 7-5).

7.3.1.1 Both Techniques Combined Velocities

Table 7-6: Descriptive statistics (mean, range, standard deviation) for the swimmers' CoM velocity at the start and end of glide 1 and fly kick phase of the BUP and the minimum/maximum and mean velocity within glide 1 and fly kick phase. Also shown is the total mean velocity of the BUP. Data are presented for the sub-elite and elite samples when techniques are combined. MANOVA was used to identify the effect of skill level on CoM velocity at the start and end of glide 1 and fly kick phase of the BUP and the minimum/maximum and mean velocity within glide 1 and fly kick phase.

Phase	Variable ($m \cdot s^{-1}$)	Sub-elite (n=14)	Elite (n=7)	p
BUP	Total mean velocity	1.31 ± 0.12	1.43 ± 0.07	.02*
		(1.04 – 1.46)	(1.34 – 1.53)	
Glide 1	End of phase velocity	1.57 ± 0.23	1.71 ± 0.20	.16
		(1.26 – 1.94)	(1.40 – 2.02)	
Fly kick - Prep/recovery	Start of phase velocity	1.57 ± 0.23	1.71 ± 0.20	.21
		(1.26 – 1.94)	(1.40 – 2.02)	
	Min velocity	1.41 ± 0.17	1.51 ± 0.13	.22
		(1.20 – 1.68)	(1.34 – 1.69)	
	Mean velocity	1.54 ± 0.20	1.61 ± 0.13	.40
		(1.26 – 1.93)	(1.45 – 1.8)	
Fly kick - down beat	Start of phase velocity	1.55 ± 0.25	1.57 ± 0.13	.87
		(1.21 – 2.16)	(1.35 – 1.73)	
	Max velocity	1.72 ± 0.26	1.75 ± 0.16	.82
		(1.40 – 2.19)	(1.59 – 2.08)	
	Mean velocity	1.63 ± 0.23	1.67 ± 0.15	.71
		(1.37 – 2.12)	(1.49 – 1.95)	
Fly kick - upbeat	Start of phase velocity	1.63 ± 0.26	1.69 ± 0.17	.62
		(1.36 – 2.20)	(1.52 – 2.05)	
	End of phase velocity	1.55 ± 0.23	1.56 ± 0.17	.88
		(1.27 – 1.91)	(1.37 – 1.90)	
	Max velocity	1.65 ± 0.27	1.72 ± 0.18	.53
		(1.36 – 2.23)	(1.52 – 2.05)	
	Mean velocity	1.59 ± 0.25	1.59 ± 0.12	.93
		(1.33 – 2.07)	(1.46 – 1.6)	

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

Table 7-7: Descriptive statistics (mean, range, standard deviation) for the swimmers' CoM velocity at the start and end of the Pull-down phase of the BUP and the minimum/maximum and mean velocity within the Pull-down phase. Data are presented for the sub-elite and elite samples when techniques are combined. MANOVA was used to identify the effect of skill level on CoM velocity at the start and end of the Pull-down phase of the BUP and the minimum/maximum and mean velocity within the Pull-down phase.

Phase	Variable ($m \cdot s^{-1}$)	Sub-elite (n=14)	Elite (n=7)	p
Pulldown	Start of phase velocity	1.39 ± 0.13	1.50 ± 0.11	.10
		(1.15 – 1.66)	(1.36 – 1.64)	
	End of phase velocity	1.94 ± 0.17	2.04 ± 0.09	.14
		(1.60 – 2.22)	(1.89 – 2.15)	
	Max velocity	1.97 ± 0.16	2.08 ± 0.10	.14
		(1.66 – 2.22)	(1.90 – 2.19)	
	Mean velocity	1.57 ± 0.12	1.71 ± 0.08	.009**
		(1.35 – 1.77)	(1.61 – 1.83)	

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

Table 7-8: Descriptive statistics (mean, range, standard deviation) for the swimmers' CoM velocity at the start and end of glide 2 phase of the BUP and the minimum/maximum and mean velocity within glide 2 phase. Data are presented for the sub-elite and elite samples when techniques are combined. MANOVA was used to identify the effect of skill level on CoM velocity at the start and end of glide 2 phase of the BUP and the minimum/maximum and mean velocity within glide 2 phase.

Phase	Variable ($m \cdot s^{-1}$)	Sub-elite (n=14)	Elite (n=7)	p
Glide 2	Start of phase velocity	1.92 ± 0.17	2.03 ± 0.09	.12
		(1.59 – 2.23)	(1.88 – 2.13)	
	End of phase velocity	1.33 ± 0.16	1.57 ± 0.11	.003*
		(1.09 – 1.59)	(1.43 – 1.71)	
	Min velocity	1.33 ± 0.16	1.57 ± 0.11	.003*
		(1.09 – 1.59)	(1.43 – 1.71)	
	Mean velocity	1.59 ± 0.14	1.77 ± 0.08	.006*
		(1.30 – 1.79)	(1.66 – 1.88)	

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

Table 7-9: Descriptive statistics (mean, range, standard deviation) for the swimmers' CoM velocity at the start and end of the Arm and leg recovery phase of the BUP and the minimum/maximum and mean velocity within the Arm and leg recovery phase. Data are presented for the sub-elite and elite samples when techniques are combined. MANOVA was used to identify the effect of skill level on CoM velocity at the start and end of the Arm and leg recovery phase of the BUP and the minimum/maximum and mean velocity within the Arm and leg recovery phase.

Phase	Variable ($m \cdot s^{-1}$)	Sub-elite (n=14)	Elite (n=7)	p
Arm and leg	Start of phase velocity	1.32 ± 0.16	1.56 ± 0.11	.003*
recovery		(1.08 – 1.58)	(1.43 – 1.70)	
	End of phase velocity	0.61 ± 0.13	0.76 ± 0.21	.06
		(0.42 - 0.82)	(0.51 – 1.09)	
	Min velocity	0.43 ± 0.09	0.50 ± 0.04	.08
		(0.29 - 0.60)	(0.44 - 0.57)	
	Mean velocity	0.88 ± .1	1.06 ± .08	<.001**
		(0.70 – 1.03)	(0.97 – 1.17)	

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

Table 7-10: Descriptive statistics (mean, range, standard deviation) for the swimmers' CoM velocity at the start and end of the kick phase of the BUP and the minimum/maximum and mean velocity within the kick phase. Data are presented for the sub-elite and elite samples when techniques are combined. MANOVA was used to identify the effect of skill level on CoM velocity at the start and end of the kick phase of the BUP and the minimum/maximum and mean velocity within the kick phase.

Phase	Variable ($m \cdot s^{-1}$)	Sub-elite (n=14)	Elite (n=7)	p
Kick	Start of phase velocity	0.46 ± 0.10	0.52 ± 0.06	.16
		(0.32 - 0.64)	(0.45 - 0.61)	
	End of phase velocity	1.21 ± 0.15	1.32 ± 0.08	.09
		(1.02 – 1.41)	(1.25 – 1.48)	
	Max velocity	1.22 ± 0.14	1.36 ± 0.10	.032*
		(1.02 – 1.41)	(1.28 – 1.57)	
	Mean velocity	0.88 ± 0.08	1.03 ± 0.07	<.001**
		(0.74 – 1.06)	(0.95 – 1.17)	

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

There was no significant effect found for skill level on overall BUP velocity and sub phase velocity, $F(18, 1) = 3.7$, $p = .39$; Wilk's lambda = 0.02, partial eta squared = .99. However, a further pairwise analysis demonstrated a significant difference between elite and sub-elite swimmers was observed in overall BUP velocity ($p=.02$), with elite swimmers displaying a larger overall velocity (Table 7-6). Elite swimmers were also found to have significantly higher velocities in the mean velocity of the Pull-down ($p<.01$) (Table 7-7), end of glide 2 velocity and minimum glide 2 velocity ($p<.01$), mean glide 2 velocity ($p<.01$) (Table 7-8), start of Arm + leg recovery velocity ($p<.01$), mean Arm + leg recovery velocity ($p<.001$) (Table 7-9) and kick maximum velocity ($p=.03$) and mean kick velocity ($p<.001$) (Table 7-10).

7.3.1.2 Separated and Overlap Technique Velocities

Table 7-11: Descriptive statistics (mean, range, standard deviation) for the swimmers' CoM velocity at the start and end of glide 1 and fly kick phase of the BUP and the minimum and maximum velocity within the glide 1 and fly kick phase. Also shown is the total mean velocity of the BUP. Data are presented for the sub-elite and elite samples. MANOVA was used to identify the effect of skill level on CoM velocity at the start and end of glide 1 and fly kick phase of the BUP and the minimum and maximum velocity within the glide 1 and fly kick phase for the separated technique.

Phase	Variable	SEPARATED		p	OVERLAP	
		Sub-elite (n=11)	Elite (n=3)		Sub-elite (n=3)	Elite (n=3)
BUP	Total mean velocity	1.34 ± 0.09	1.48 ± 0.05	.02*	1.20 ± 0.17	1.38 ± 0.04
		(1.14 – 1.46)	(1.41 – 1.53)		(1.04 – 1.37)	(1.34 – 1.40)
Glide 1	End of phase velocity	1.61 ± 0.22	1.83 ± 0.14	.10	1.39 ± 0.14	1.55 ± 0.14
		(1.32 – 1.94)	(1.70 – 2.02)		(1.26 – 1.53)	(1.40 – 1.67)
Fly kick - Prep/recovery	Start of phase velocity	1.61 ± 0.22	1.83 ± 0.14	.13	1.36 ± 0.15	1.55 ± 0.14
		(1.32 – 1.94)	(1.70 – 2.02)		(1.26 – 1.53)	(1.40 – 1.67)
	Min velocity	1.45 ± 0.18	1.60 ± 0.07	.12	1.29 ± 0.04	1.38 ± 0.06
		(1.20 – 1.68)	(1.55 – 1.69)		(1.26 – 1.34)	(1.34 – 1.45)
	Mean velocity	1.57 ± 0.22	1.69 ± 0.10	.30	1.45 ± 0.03	1.50 ± 0.05
		(1.26 – 1.93)	(1.62 – 1.83)		(1.42 – 1.47)	(1.45 – 1.54)
Fly kick - down beat	Start of phase velocity	1.52 ± 0.29	1.61 ± 0.06	.58	1.63 ± 0.04	1.51 ± 0.20
		(1.21 – 2.16)	(1.55 – 1.67)		(1.59 – 1.67)	(1.35 – 1.73)
	Max velocity	1.64 ± 0.23	1.73 ± 0.04	.47	1.99 ± 0.16	1.77 ± 0.27
		(1.4 – 2.19)	(1.67 – 1.76)		(1.85 – 2.16)	(1.59 – 2.08)
	Mean velocity	1.58 ± 0.23	1.67 ± 0.04	.43	1.83 ± 0.05	1.67 ± 0.25
		(1.37 – 2.12)	(1.62 – 1.70)		(1.77 – 1.87)	(1.49 – 1.95)
Fly kick - upbeat	Start of phase velocity	1.53 ± 0.19	1.66 ± 0.03	.24	1.97 ± 0.20	1.74 ± 0.28
		(1.36 – 2.00)	(1.63 – 1.69)		(1.84 – 2.20)	(1.52 – 2.05)
	End of phase velocity	1.48 ± 0.22	1.49 ± 0.10	.94	1.77 ± 0.12	1.66 ± 0.21
		(1.27 – 1.91)	(1.37 – 1.62)		(1.63 – 1.86)	(1.50 – 1.90)
	Max velocity	1.56 ± 0.20	1.65 ± .02	.37	1.98 ± 0.22	1.82 ± 0.27
		(1.36 – 2.00)	(1.63 – 1.67)		(1.84 – 2.23)	(1.52 – 2.05)
	Mean velocity	1.50 ± 0.20	1.55 ± 0.06	.64	1.88 ± 0.17	1.66 ± 0.17
		(1.33 – 1.95)	(1.50 – 1.62)		(1.74 – 2.07)	(1.46 – 1.76)

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

There was no significant effect found for skill level on overall BUP velocity and sub phase velocity for the separated technique, $F(12, 1) = 10.53$, $p = .24$; Wilk's lambda = .01, partial eta squared = 0.99. However, a further pairwise analysis demonstrated a significant difference between elite and sub-elite swimmers for the overall BUP velocity (p=.02), with elite swimmers displaying a larger overall velocity (Table 7-11).

Table 7-12: Descriptive statistics (mean, range, standard deviation) for the swimmers' CoM velocity at the start and end of Pull-down phase of the BUP and the minimum and maximum velocity within the Pull-down phase. Data are presented for the sub-elite and elite samples. MANOVA was used to identify the effect of skill level on CoM velocity at the start and end of Pull-down phase of the BUP and the minimum and maximum velocity within the Pull-down phase for the separated technique.

Phase	Variable	SEPARATED		p	OVERLAP	
		Sub-elite (n=11)	Elite (n=4)		Sub-elite (n=3)	Elite (n=3)
Pulldown	Start of phase velocity	1.41 ± 0.15	1.51 ± 0.13	.26	1.34 ± 0.07	1.48 ± 0.10
		(1.15 – 1.66)	(1.36 – 1.64)		(1.26 – 1.39)	(1.40 – 1.59)
	End of phase velocity	1.93 ± 0.16	2.09 ± 0.07	.09	1.97 ± 0.22	1.99 ± 0.09
		(1.60 – 2.13)	(1.99 – 2.15)		(1.84 – 2.22)	(1.89 – 2.07)
	Max velocity	1.96 ± 0.16	2.13 ± 0.08	.07	2.02 ± 0.19	2.00 ± 0.09
		(1.66 – 2.19)	(2.03 – 2.19)		(1.85 – 2.22)	(1.90 – 2.08)
	Mean velocity	1.58 ± 0.12	1.74 ± 0.07	.03*	1.52 ± 0.10	1.67 ± 0.08
		(1.35 – 1.77)	(1.66 – 1.83)		(1.43 – 1.62)	(1.61 – 1.76)

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

Additionally, a further pairwise analysis demonstrated a significantly higher mean velocity of the Pull-down by the elite group (p=.03) (Table 7-12).

Table 7-13: Descriptive statistics (mean, range, standard deviation) for the swimmers' CoM velocity at the start and end of 2nd Glide phase of the BUP and the minimum and maximum velocity within the 2nd Glide phase. Data are presented for the sub-elite and elite samples. MANOVA was used to identify the effect of skill level on CoM velocity at the start and end of 2nd Glide phase of the BUP and the minimum and maximum velocity within the 2nd Glide phase for the separated technique.

Phase	Variable	SEPARATED		p	OVERLAP	
		Sub-elite (n=11)	Elite (n=4)		Sub-elite (n=3)	Elite (n=3)
Glide 2	Start of phase velocity	1.91 ± 0.15	2.08 ± 0.07	.06	1.96 ± 0.23	1.97 ± 0.09
		(1.59 – 2.10)	(1.98 – 2.13)		(1.81 – 2.23)	(1.88 – 2.05)
	End of phase velocity	1.37 ± 0.17	1.61 ± 0.13	.03*	1.20 ± 0.06	1.53 ± 0.08
		(1.09 – 1.59)	(1.45 – 1.71)		(1.14 – 1.25)	(1.43 – 1.58)
	Min velocity	1.37 ± 0.17	1.61 ± 0.13	.03*	1.20 ± 0.06	1.53 ± 0.08
		(1.09 – 1.59)	(1.45 – 1.71)		(1.14 – 1.25)	(1.43 – 1.58)
	Mean velocity	1.61 ± 0.14	1.82 ± 0.06	.02*	1.51 ± 0.14	1.71 ± 0.05
		(1.30 – 1.79)	(1.73 – 1.88)		(1.40 – 1.67)	(1.66 – 1.76)

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

Additionally, however, a further pairwise analysis demonstrated a significant difference between elite and sub-elite swimmers for the end of glide 2 velocity (p=.03), minimum glide 2 velocity (p=.03), mean glide 2 velocity (p=.02), with elite swimmers displaying higher velocities in all glide 2 variables (Table 7-13).

Table 7-14: Descriptive statistics (mean, range, standard deviation) for the swimmers' CoM velocity at the start and end of the Arm and leg recovery phase of the BUP and the minimum and maximum velocity within the Arm and leg recovery phase. Data are presented for the sub-elite and elite samples. MANOVA was used to identify the effect of skill level on CoM velocity at the start and end of the Arm and leg recovery phase of the BUP and the minimum and maximum velocity within the Arm and leg recovery phase for the separated technique.

Phase	Variable	SEPARATED		p	OVERLAP	
		Sub-elite (n=11)	Elite (n=4)		Sub-elite (n=3)	Elite (n=3)
Arm and leg recovery	Start of phase velocity	1.36 ± 0.17 (1.08 – 1.58)	1.59 ± 0.13 (1.43 – 1.70)	.03*	1.20 ± 0.06 (1.14 – 1.25)	1.52 ± 0.08 (1.43 – 1.57)
	End of phase velocity	0.63 ± 0.13 (0.42 - 0.82)	0.62 ± 0.12 (0.51 - 0.74)	.96	0.56 ± 0.16 (0.42 - 0.73)	0.95 ± 0.15 (0.79 – 1.09)
	Min velocity	0.43 ± 0.1 (0.29 - 0.6)	0.51 ± 0.05 (0.44 - 0.57)	.19	0.42 ± 0.09 (0.36 - 0.53)	0.49 ± 0.03 (0.46 - 0.52)
	Mean velocity	0.89 ± .1 (0.7 – 1.03)	1.11 ± 0.08 (1.01 – 1.17)	.002**	0.83 ± 0.06 (0.79 - 0.9)	1 ± 0.02 (0.97 – 1.01)

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

A further pairwise analysis demonstrated a significantly larger velocity for elite swimmers than sub-elite swimmers for the start of Arm + leg recovery ($p=.03$), and mean Arm + leg recovery velocity ($p<.01$) (Table 7-14).

Table 7-15: Descriptive statistics (mean, range, standard deviation) for the swimmers' CoM velocity at the start and end of the kick phase of the BUP and the minimum and maximum velocity within the kick phase. Data are presented for the sub-elite and elite samples. MANOVA was used to identify the effect of skill level on CoM velocity at the start and end of the kick phase of the BUP and the minimum and maximum velocity within the kick phase for the separated technique.

Phase	Variable	SEPARATED		p	OVERLAP	
		Sub-elite (n=11)	Elite (n=4)		Sub-elite (n=3)	Elite (n=3)
Kick	Start of phase	0.47 ± 0.11	0.54 ± 0.07	.26	0.44 ± 0.08	0.5 ± 0.03
	velocity	(0.32 - 0.64)	(0.45 - 0.61)		(0.39 - 0.53)	(0.47 - 0.53)
	End of phase	1.24 ± 0.14	1.30 ± 0.03	.33	1.12 ± 0.16	1.35 ± 0.12
	velocity	(1.02 – 1.41)	(1.26 – 1.34)		(1.02 – 1.30)	(1.25 – 1.48)
	Max velocity	1.25 ± 0.13	1.32 ± 0.05	.44	1.13 ± -0.16	1.42 ± 0.14
		(1.06 – 1.41)	(1.28 - 1.38)		(1.02 – 1.31)	(1.31 – 1.57)
	Mean velocity	0.90 ± 0.08	0.99 ± 0.04	.04*	0.82 ± 0.07	1.09 ± 0.07
		(0.81 – 1.06)	(0.95 – 1.03)		(0.74 - 0.88)	(1.04 – 1.17)

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

A further pairwise analysis demonstrated a significantly higher mean kick velocity for the elite group (p=.04) (Table 7-15).

7.3.1.3 Both Techniques Combined Distances

Table 7-16: Descriptive statistics (mean, range, standard deviation) for the swimmers' CoM distance at the start and end of each phase of the BUP and the distance gained within each phase. Also shown is the breakout distance of the BUP. Data are presented for the sub-elite and elite samples when both techniques are combined. MANOVA was used to identify the effect of skill level on CoM distance at the start and end of each phase of the BUP and the distance gained within each phase and breakout distance for when both techniques were combined.

Phase	Variable	Sub-elite (n=14)	Elite (n=7)	p
BUP Total	Breakout distance	8.84 ± 1.00 (7.08 – 10.66)	9.43 ± 0.74 (8.51 – 10.41)	.19
Glide	End of phase distance	3.80 ± 0.60 (2.92 – 5.13)	3.95 ± 0.48 (3.50 – 4.74)	.58
Fly kick - Prep/recovery	Start of phase distance	3.80 ± 0.70 (2.92 – 5.13)	3.95 ± 0.48 (3.50 – 4.74)	.93
	Distance Gain	0.60 ± 0.17 (0.29 - 0.85)	0.79 ± 0.13 (0.61 – 1.02)	.02*
Fly kick - Downbeat	Start of phase distance	4.52 ± 0.71 (3.51 – 5.86)	4.77 ± 0.46 (4.36 – 5.48)	.41
	Distance Gain	0.38 ± 0.07 (0.28 - 0.51)	0.36 ± 0.02 (0.34 - 0.39)	.33
Fly kick - Upbeat	Start of phase distance	4.94 ± 0.73 (3.84 – 6.4)	5.17 ± 0.48 (4.74 – 5.91)	.47
	Distance Gain	0.34 ± 0.16 (0.07 - 0.71)	0.51 ± 0.23 (0.28 - 0.95)	.07
Pull-down	Start of phase distance	4.77 ± 0.77 (3.77 – 6.23)	5.09 ± 0.68 (4.30 – 5.91)	.37
	Distance Gain	1.19 ± 0.19 (0.88 – 1.52)	1.28 ± 0.22 (1.06 – 1.73)	.34
Glide 2	Start of phase distance	5.99 ± 0.84 (5.09 – 7.55)	6.41 ± 0.64 (5.58 – 7.31)	.27

	Distance Gain	1.39 ± 0.47	1.08 ± 0.31	.14
		(0.59 – 1.99)	(0.67 – 1.45)	
Arm and leg recovery	Start of phase distance	7.41 ± 0.96	7.53 ± 0.79	.78
		(5.94 – 9.56)	(6.89 – 8.75)	
	Distance Gain	0.86 ± 0.17	1.16 ± 0.19	.002**
		(0.64 – 1.17)	(0.94 – 1.44)	
Kick	Start of phase distance	8.22 ± 0.95	8.62 ± 0.93	.38
		(6.66 – 10.29)	(7.72 – 10.01)	
	End of phase distance	8.61 ± 0.97	9.10 ± 0.84	.27
		(7.08 – 10.66)	(8.32 – 10.41)	
	Distance Gain	0.39 ± 0.07	0.48 ± 0.09	.03*
		(0.24 - 0.47)	(0.38 - 0.59)	

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

When both techniques are combined, there was no significant effect found for skill level on BUP breakout distance and sub phase distances for the separated technique, $F(18, 1) = .45$, $p = .85$; Wilk's lambda = .11, partial eta squared = 0.89.

However, a further pairwise analysis demonstrated a significant difference between elite and sub-elite swimmers was observed in Fly kick prep/recovery distance gained ($p=.02$), distance gained in the Arm + leg recovery ($p<.01$) and kick distance gained ($p=.03$), with elite swimmers gaining greater distances than sub-elite swimmers (Table 7-16).

7.3.1.4 Separated and Overlap Technique Distances

Table 7-17: Descriptive statistics (mean, range, standard deviation) for the swimmers' CoM distance at the start and end of the glide and fly kick phase the BUP and the distance gained within the phases. Also shown is the breakout distance of the BUP. Data are presented for the sub-elite and elite samples for the separated and overlap techniques. MANOVA was used to identify the effect of skill level on CoM distance at the start and end of the glide and fly kick phase the BUP and the distance gained within the phases for the separated technique.

Phase	Variable	SEPARATED		p	OVERLAP	
		Sub-elite (n=11)	Elite (n=4)		Sub-elite (n=3)	Elite (n=3)
BUP Breakout Distance		8.93 ± 1.10	9.88 ± 0.63	.13	8.57 ± 0.36	8.82 ± 0.23
		(7.08 – 10.66)	(9.12 – 10.41)		(7.90 – 9.02)	(8.51 – 9.05)
Glide	End of phase	3.77 ± 0.69	3.90 ± 0.41	.73	3.90 ± 0.14	4.02 ± 0.65
	distance	(2.92 – 5.13)	(3.6 – 4.48)		(3.77 – 4.04)	(3.5 – 4.74)
Fly kick -	Start of phase	3.84 ± 0.78	3.90 ± 0.41	.87	4.23 ± 0.16	4.02 ± 0.65
Prep/recovery	distance	(2.92 – 5.13)	(3.6 – 4.48)		(4.04 – 4.35)	(3.5 – 4.74)
	Distance Gain	0.65 ± 0.13	0.85 ± 0.13	.02*	0.46 ± 0.24	0.71 ± 0.11
		(0.43 - 0.85)	(0.72 – 1.02)		(0.29 - 0.74)	(0.61 - 0.83)
Fly kick -	Start of phase	4.46 ± 0.81	4.78 ± 0.41	.47	4.72 ± 0.10	4.76 ± 0.62
Downbeat	distance	(3.51 – 5.86)	(4.38 – 5.35)		(4.62 – 4.81)	(4.36 – 5.48)
	Distance Gain	0.39 ± 0.07	0.35 ± 0.02	.38	0.38 ± 0.05	0.37 ± 0.02
		(0.28 - 0.51)	(0.34 - 0.37)		(0.32 - 0.41)	(0.35 - 0.39)
Fly kick - Upbeat	Start of phase	4.88 ± 0.83	5.17 ± 0.42	.52	5.14 ± 0.10	5.16 ± 0.65
	distance	(3.84 – 6.40)	(4.77 – 5.75)		(5.07 – 5.26)	(4.74 – 5.91)
	End of phase	5.21 ± 0.81	5.66 ± 0.46	.33	5.51 ± 0.41	5.71 ± 1.00
	distance	(4.11 – 6.57)	(5.08 – 6.18)		(5.16 – 5.96)	(5.02 – 6.86)
	Distance Gain	0.33 ± 0.09	0.49 ± 0.14	.03*	0.38 ± 0.32	0.54 ± 0.36
		(0.17 - 0.51)	(0.31 - 0.63)		(0.07 - 0.71)	(0.28 - 0.95)

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

Table 7-18: Descriptive statistics (mean, range, standard deviation) for the swimmers' CoM distance at the start and end of the Pull-down phase of the BUP and the distance gained within the phase. Also shown is the breakout distance of the BUP. Data are presented for the sub-elite and elite samples for the separated and overlap techniques. MANOVA was used to identify the effect of skill level on CoM distance at the start and end of the Pull-down phase of the BUP and the distance gained within the phase for the separated technique.

Phase	Variable	SEPARATED		p	OVERLAP	
		Sub-elite (n=11)	Elite (n=4)		Sub-elite (n=3)	Elite (n=3)
Pull-down	Start of phase	5.00 ± 0.72	5.47 ± 0.66	.28	4.00 ± 0.29	4.58 ± 0.24
	distance	(4.37 – 6.23)	(4.50 – 5.91)		(3.77 – 4.33)	(4.30 – 4.74)
	End of phase	6.20 ± 0.81	6.82 ± 0.43	.18	5.15 ± 0.13	5.78 ± 0.21
	distance	(5.29 – 7.51)	(6.23 – 7.27)		(5.05 – 5.30)	(5.54 – 5.94)
	Distance Gain	1.20 ± 0.21	1.34 ± 0.28	.3	1.15 ± 0.16	1.20 ± 0.07
		(0.88 – 1.52)	(1.06 – 1.73)		(0.97 – 1.28)	(1.12 – 1.24)

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

Table 7-19: Descriptive statistics (mean, range, standard deviation) for the swimmers' CoM distance at the start and end of glide 2 of the BUP and the distance gained within the phase. Also shown is the breakout distance of the BUP. Data are presented for the sub-elite and elite samples for the separated and overlap techniques. MANOVA was used to identify the effect of skill level on CoM distance at the start and end of glide 2 of the BUP and the distance gained within the phase for the separated technique.

Phase	Variable	SEPARATED		p	OVERLAP	
		Sub-elite (n=11)	Elite (n=4)		Sub-elite (n=3)	Elite (n=3)
Glide 2	Start of phase	6.23 ± 0.81	6.86 ± 0.43	.18	5.19 ± 0.13	5.82 ± 0.21
	distance	(5.32 – 7.55)	(6.27 – 7.31)		(5.09 – 5.34)	(5.58 – 5.98)
	End of phase	7.58 ± 1	7.96 ± 0.77	.51	6.75 ± 0.44	6.89 ± 0.04
	distance	(5.91 – 9.54)	(6.94 – 8.72)		(6.33 – 7.20)	(6.86 – 6.94)
	Distance Gain	1.34 ± 0.51	1.10 ± 0.39	.42	1.56 ± 0.31	1.06 ± 0.26
		(0.59 – 1.99)	(0.67 – 1.45)		(1.24 - 1.86)	(0.88 – 1.36)

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

Table 7-20: Descriptive statistics (mean, range, standard deviation) for the swimmers' CoM distance at the start and end of the Arm and leg recovery phase of the BUP and the distance gained within the phase. Also shown is the breakout distance of the BUP. Data are presented for the sub-elite and elite samples for the separated and overlap techniques. MANOVA was used to identify the effect of skill level on CoM distance at the start and end of the Arm and leg recovery phase of the BUP and the distance gained within the phase for the separated technique.

Phase	Variable	SEPARATED		p	OVERLAP	
		Sub-elite (n=11)	Elite (n=4)		Sub-elite (n=3)	Elite (n=3)
Arm and leg	Start of phase	7.60 ± 1	7.99 ± 0.77	.51	6.76 ± 0.43	6.92 ± 0.04
recovery	distance	(5.94 – 9.56)	(6.97 – 8.75)		(6.35 – 7.20)	(6.89 – 6.96)
	End of phase	8.46 ± 1.02	9.3 ± 0.71	.16	7.64 ± 0.18	7.89 ± 0.06
	distance	(6.71 – 10.32)	(8.42 – 10.07)		(7.52 – 7.85)	(7.84 – 7.95)
	Distance Gain	0.86 ± 0.16	1.30 ± 0.10	.00**	0.88 ± 0.27	0.98 ± 0.03
		(0.64 – 1.17)	(1.21 – 1.44)		(0.65 – 1.17)	(0.94 - 1)

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

Table 7-21: Descriptive statistics (mean, range, standard deviation) for the swimmers' CoM distance at the start and end of the kick phase of the BUP and the distance gained within the phase. Also shown is the breakout distance of the BUP. Data are presented for the sub-elite and elite samples for the separated and overlap techniques. MANOVA was used to identify the effect of skill level on CoM distance at the start and end of the kick phase of the BUP and the distance gained within the phase for the separated technique.

Phase	Variable	SEPARATED		p	OVERLAP	
		Sub-elite (n=11)	Elite (n=4)		Sub-elite (n=3)	Elite (n=3)
Kick	Start of phase	8.41 ± 1.02	9.24 ± 0.71	.16	7.60 ± 0.21	7.79 ± 0.07
	distance	(6.66 – 10.29)	(8.34 – 10.01)		(7.48 – 7.85)	(7.72 – 7.86)
	End of phase	8.79 ± 1.04	9.65 ± 0.69	.16	7.98 ± 0.22	8.36 ± 0.06
	distance	(7.08 – 10.66)	(8.79 – 10.41)		(7.81 – 8.22)	(8.32 – 8.43)
	Distance Gain	0.39 ± 0.08	0.40 ± 0.03	.74	0.38 ± 0.04	0.57 ± 0.02
		(0.24 - 0.47)	(0.38 - 0.45)		(0.34 - 0.42)	(0.56 - 0.59)

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

When the separated technique is looked at solely, there was no significant effect found for skill level on BUP breakout distance and sub phase distances for the separated technique, F(4, 1) = .45, p = .89; Wilk's lambda = .51, partial eta squared = 0.49.

However, a further pairwise analysis demonstrated a significant difference between elite and sub-elite swimmers was observed in Fly kick prep/recovery distance gained (p=.02) and Fly kick upbeat distance gained (p=.03) (Table 7-17), Arm + leg recovery distance gained (p<.000) (Table 7-20), with elite swimmers gaining greater distances than sub-elite swimmers.

7.3.2 CoM Trajectories

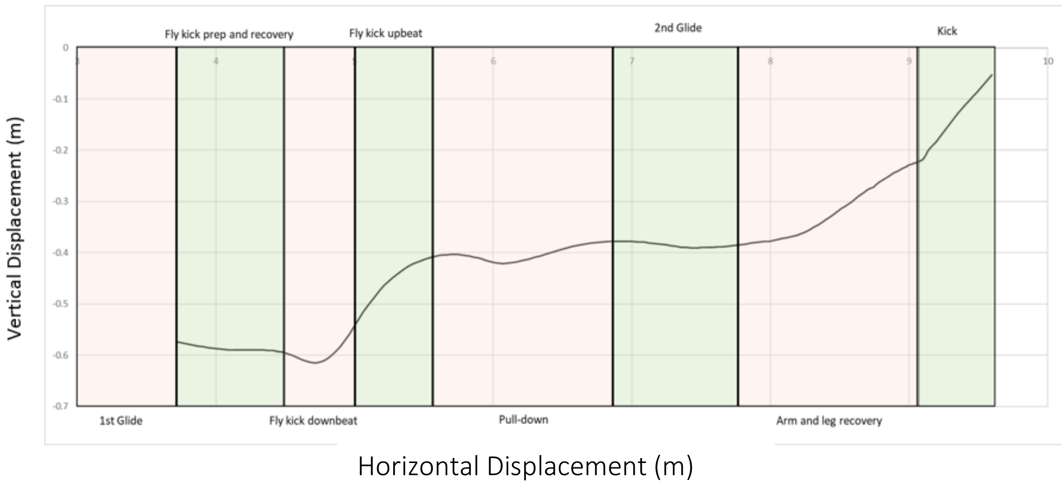


Figure 7.1: CoM trajectory a single BUP with identified phases of the fastest participant to 10 m

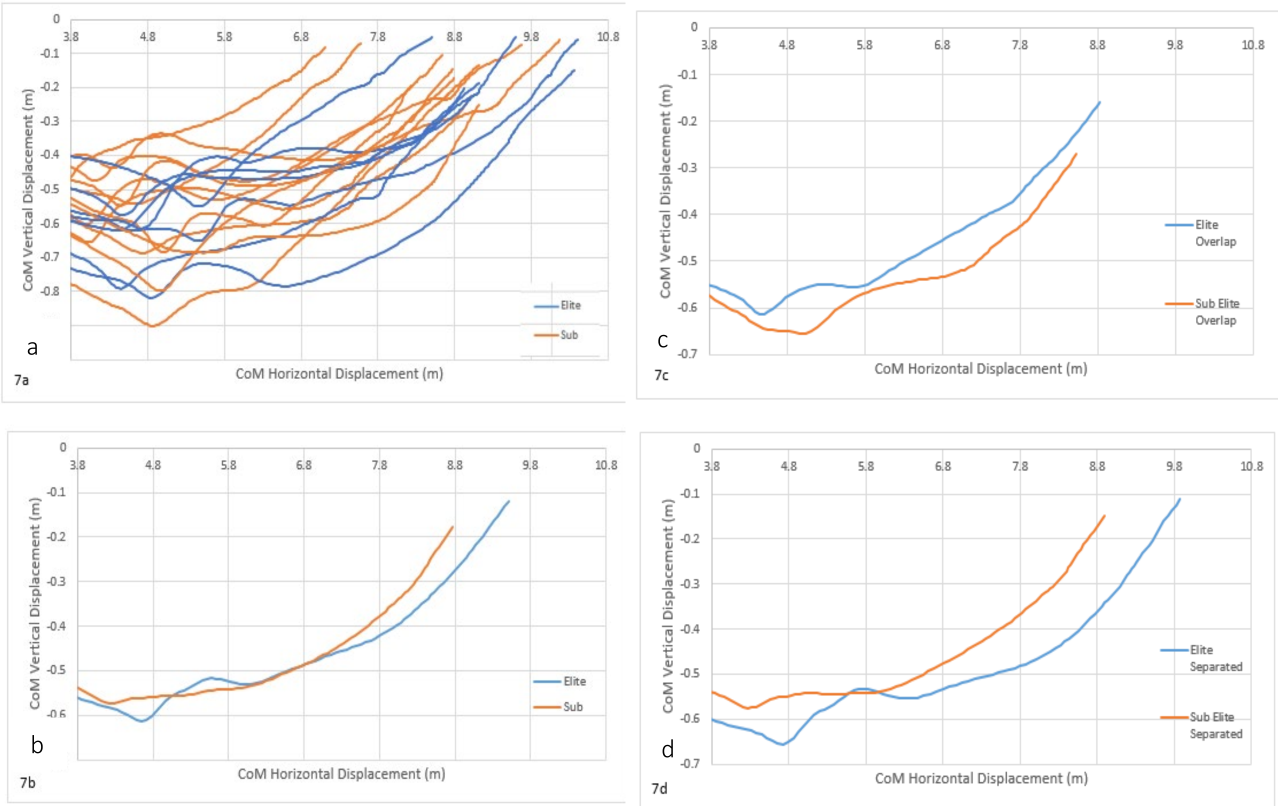


Figure 7.2: a) Individual CoM trajectory of BUP for all participants, b) Mean CoM trajectories of both techniques BUP for elite and sub-elite samples, c) Mean CoM trajectories of the separated technique BUP for elite and sub-elite samples, d) Mean CoM trajectories of the overlap technique BUP for elite and sub-elite samples

Figure 7-2b shows that when not divided by technique, elite swimmers on average reach a greater vertical displacement (travel deeper) than sub-elite swimmers however they make a large change in direction of travel around 20 – 30% of the stroke.

Figure 7-2c shows similar patterns when divided into the separated technique, with elite swimmers on average display a larger vertical displacement throughout the BUP with the largest vertical displacement of .66 m post first glide. Additionally, a much larger fluctuation of the trajectory is performed by elite swimmers with elite swimmers making a large change in direction of travel around 20 – 30% of the stroke.

Figure 7-2d contradictory to the figures 7-2b and 7-2c, when divided into the overlap technique, sub-elite swimmers on average display a larger vertical displacement throughout the BUP with the largest vertical displacement of .66 m post first glide and commence the breakout much deeper.

7.3.3 Horizontal velocity variation

Table 7-22: Intra-cyclic velocity variations throughout the BUP (%).

	IVV (%)
Elite	25.9
Sub-elite	28.1
p	0.01*

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

When looking into the IVV (%) between elite and sub-elite swimmers a significant difference was found (p=0.011), with a large main effect size 2.22(Table 7-22).

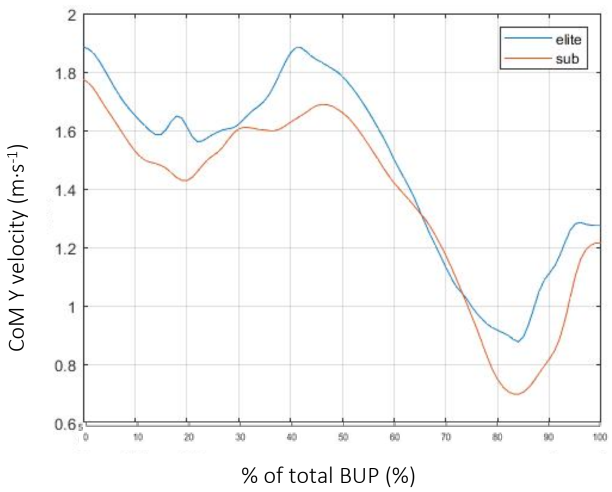


Figure 7-3a

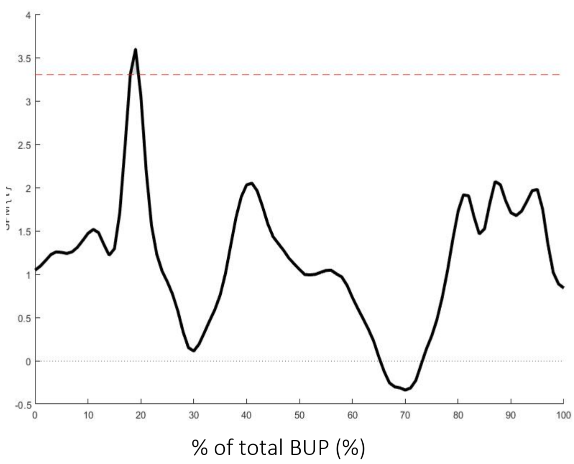


Figure 7-3b

Figure 7-3: a) Mean BUP CoM horizontal (y) velocity for elite (blue, n= 7) and sub-elite (orange, n= 13) swimmers. 27b) Paired samples t-test statistic SPM {t}. The critical threshold of 3.306 is denoted by the red dashed line.

The mean CoM velocity during the BUP of elite and sub-elite swimmers were highly similar for the majority of time (figure 7-3a). However, one supra-threshold cluster (18-19.5%) exceeded the critical threshold of 3.31 indicating that the mean CoM velocity of the elite swimmers was significantly higher than that of the sub-elite swimmers (figure 7-3b). The 18-19.5% aligns with the fly kick placement. The precise probability that a supra-threshold cluster of this size would be observed in repeated random samplings was p= 0.045.

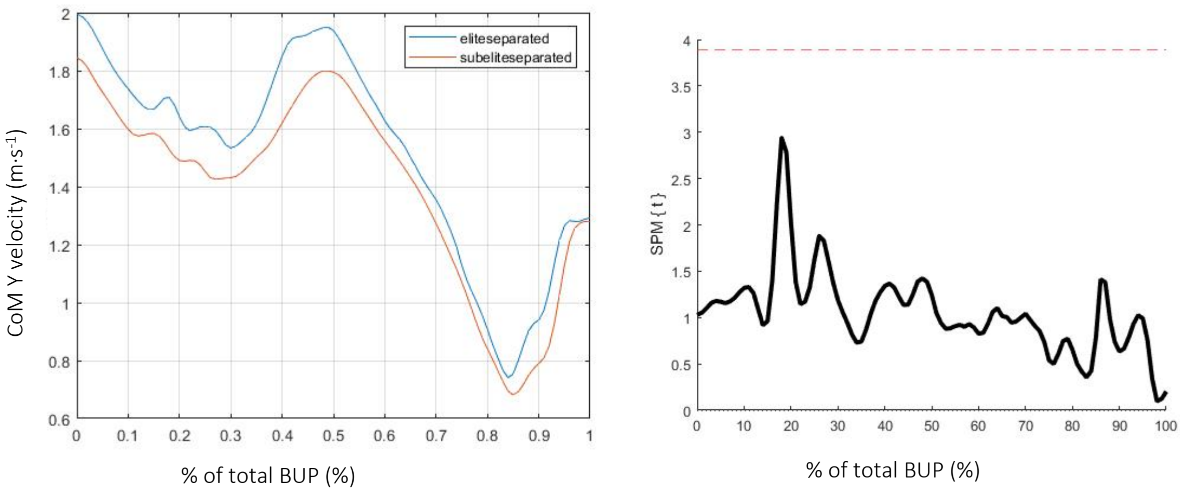


Figure 7-4a Figure 7-4b

Figure 7-4: a) Mean BUP CoM velocities for elite separated (blue, n=4) and sub-elite separated (orange, n= 10) swimmers. b) Paired samples t-test statistic SPM {t}. The critical threshold of 3.89 is denoted by the red dashed line.

The mean CoM velocity profiles of elite and sub-elite swimmers who used the separated BUP style showed a similar pattern. The elite swimmers showed a higher mean velocity throughout the BUP (Figure 7-4a) but at no time during the BUP did the velocity difference reach the critical threshold of 3.89 (Figure 7-4b).

7.4 Discussion

The current study aimed to identify velocity and distances variables from the BUP that correlate to 10 m time performance and to compare the CoM profiles of elite and sub-elite breaststroker underwater performance in relation to mean velocity. It was hypothesised that elite breaststroke swimmers would result in a higher mean velocity and fewer velocity fluctuations throughout the BUP.

Through previous findings in this thesis identifying significant temporal differences between the overlap and separated BUP techniques, statistical analysis was completed on separated techniques, with descriptive statistics being performed on the overlap technique due to a small sample size.

Correlations were found between multiple sub phase start, end, mean and min/maximum velocities and 10 m times with strong correlations being found for total BUP mean velocity, Fly kick preparation phase minimum velocity, Pull-down and glide 2 start and end velocities, maximum Pull-down velocity, mean Arm and leg recovery velocity and max kick velocity. Minimal research has been completed into the correlation of breaststroke underwater sub phases and a performance metric such as 10/15 m time, however Sánchez, Arellano and Cuenca-Fernández (2021) did find an identical correlation to this study of -.85 between total BUP mean velocity and 10 m and overall race time in the 50 m and 100 m short course breaststroke. Additionally, this is in agreement with Cossor and Mason (2001) and Guimaraes and Hay (1985). Who state that based of this result coaches should optimise the underwater phases of start and turns on breaststroke performance, specifically in short-course swimming however give no method of how coaches should or could optimise the underwater phase. Whereas this study highlights that focus points of propulsion to obtain a faster underwater performance should be the Pull-down maximum velocity, with the start and end 2nd glide velocities and mean velocity throughout the Arm + leg recovery being considered during the more resistive phases.

In addition to velocities breakout distance, Fly kick preparation phase distance gained, Arm + leg recovery end of phase distance and Arm + leg recovery minimum velocity distance were all found to be strongly correlated to 10 m time. This correlation with breakout distance and 10 m time concurs with Cossor and Mason (2001) who found a negative correlation of breakout distance to start time in in the women’s 200 m breaststroke and turn time in the men’s 200 m breaststroke.

When comparing elite and sub-elite breaststrokers, it was found aligned to the hypothesis that elite breaststroke swimmers were found to show a higher overall mean velocity and higher velocities within each sub phase. This is contradictory to

Gonjo and Olstad who found no differences between the levels were observed for pull-out velocity. A potential reason for this could be the standard of participants included in the studies. Gonjo and Olstad (2021) defined their elite sample as swimmers who had FINA points scores of 700 points or above however the elite sample in this currently study all had FINA points of above 800 with a mean point score of 932, significantly higher than Gonjo and Olstad (2021).

The pull-out mean velocities for elite swimmers were in agreement with Gonjo and Olstad (2021) with sub-elite swimmers in this study being found to be 0.11 $m \cdot s^{-1}$ slower than Gonjo and Olstad (2021). These differing values were not expected due to the higher calibre of athlete included in this study however the differing methods of velocity calculation may have affected these results. As stated in this thesis and other studies, although comparable patterns exist, the forward swimming velocity being defined as the rate at which the horizontal head displacement changed with time Gonjo and Olstad (2021) and the CoM horizontal velocity do differ.

A further contradictory point was that Gonjo and Olstad found elite swimmers displayed a faster glide velocity after all turns than the sub-elite swimmers, suggesting the elite sample produces a higher push-off velocity. Although similar trends were found for the BUP in this study the start of the 1st glide velocity was not calculated, with no significant difference being observed for the end of the 1^{st} glide velocity.

Specifically, when broken into sub phases, elite breaststroke swimmers were found to achieve significantly higher mean velocities ($m \cdot s^{-1}$) during the propulsive phases of the Pull-down and breaststroke kick than sub-elite swimmers. As Gonjo and Olstad (2021) found that elite swimmers are characterised by higher, clean-swimming velocity and with the complexity and similarity to a free-swimming breaststroke kick, elite breaststroke swimmers could produce a greater angular velocity during the early propulsive phase of the kick contributing to an overall greater hip speed (Matheson *et al*., 2011). Consequently, they may have the ability to apply this technique to their underwater kick (Matheson *et al*., 2011) therefore produce a higher velocity within this phase than sub-elite breaststroke swimmers.

Additionally, elite breaststroke swimmers were found to achieve significantly higher mean velocity ($m \cdot s^{-1}$) during the most resistive phase of the BUP, the Arm + leg recovery. Although maximising propulsion can contribute to the improvement of BUP performance, reducing drag and minimising the loss of horizontal velocity within the glide and resistive phases will also see an improvement in BUP performance (Figueiredo *et al*., 2012; Zhan *et al*., 2014). This study supports this statement finding that elite swimmers hold a significantly higher mean 2nd glide velocity, finish the phase with a higher velocity and additionally have a significantly higher minimum velocity within the glide.

If swimmers minimise the loss of horizontal velocity within the gliding and resistive phases, they will have the ability to maintain a higher horizontal velocity throughout the resistive phases consequently achieving a higher velocity prior to initiating the propulsive phase (Breed and McElroy, 2000). Therefore, the significant ability of the elite sample in this study to commence the recovery with a higher velocity and maintain a higher velocity within the Arm + leg recovery could be seen as a determining factor to BUP performance and could impact the significant velocity achieved within the kick.

In addition to velocity, results also found a significant difference between elite and sub-elite swimmers in the distance travelled during the whole BUP, Fly kick prep/recovery distance gained, Fly kick upbeat distance gained and Arm + leg recovery distance gained. With elite swimmers travelling 0.95 m further during the BUP than sub-elite swimmers, 0.44 m of which was in the Arm + leg recovery phase. These results were mirrored in research by Veiga *et al. (*2014a) and Cala, Frutos and Navarro (2014b) who stated that higher level swimmers travel for longer and further out of a turn in all strokes bar freestyle and therefore highlight that the elongation of the BUP for swimmers could improve their turn time and overall race time by 0.1 - 0.2 s, depending on the event.

Ruschel *et al. (*2007) however, stated that although the swimmer may have an advantage swimming underwater, it is not always beneficial for a swimmer to spend a large amount of time underwater, they must minimise the loss of horizontal velocity and maximise the propulsion during the underwater phase to travel further in a shorter time. Veiga, Roig & Gómez-Ruano (2016) found that when focusing specifically on breaststroke at the 2013 World Championships, faster swimmers did not necessarily spend a longer duration underwater than slower swimmers in the 100m breaststroke.

When comparing the mean velocities in this study to previous research, Gonjo and Olstad (2021) defined the pull-out as the combination of the fly kick and Pull-down whereas in the current study this was separated in to different skills. When combined, the mean velocities for sub-elite swimmers (1.51 $m \cdot s^{-1}$) are however slightly higher yet comparable to Gonjo and Olstad (2021), who found that over 3 short course turns of a 100 m breaststroke, sub-elite swimmers achieved a velocity of between 1.44 – 1.47 $m \cdot s^{-1}$. The elite sample in this study however recorded mean velocities of 0.15 $m \cdot s^{-1}$ faster throughout the pull out (as defined by Gonjo and Olstad (2021) than Gonjo and Olstad (2021). Although the velocities in this study are higher than previous research, the distances recorded by the participants are agreeable. In comparison to the ranges recorded over 3 turns of a short course 100 m breaststroke race simulation (Elite = 4.46 - 5.13 m, Sub-elite = 4.06 - 4.44 m) (Gonjo and Olstad, 2021) distances found in this study fall within both the elite and sub-elite ranges (Elite = 4.654 m, Sub-elite = 4.432 m).

Based on the results showing elite breaststrokers to have a significantly faster velocity in the Arm + leg recovery and travel significantly further, it could be hypothesised that elite breaststrokers have the ability to reduce the loss in CoM velocity within this resistive phase through adopting less resistive positions not through changing the time spent in the phase.

A secondary aim was to identify any differences between the velocity-time profiles of elite and non-elite breaststroke swimmers utilising SPM. This study compared the velocity-time series data through SPM. With the descriptive statistics above, it was hypothesised that a significance difference would be found around the Arm + leg recovery and the breaststroke kick, however although a large difference did exist, it was not deemed to be significant. The area of the velocity-time profile that was found to exceed the critical threshold was between 18-19.5% of the profile and identified the mean CoM velocity for elite swimmers was significantly more positive than sub-elite swimmers. The 18-19.5% aligns with the fly kick placement. Through the understanding of the temporal patterns of elite and sub-elite swimmers found in chapter 6, it was identified that some swimmers performed an overlap technique which was performed by delaying the fly kick and performing it in combination with the Pull-down. Consequently, it is believed that although magnitude of the fly kick will have contributed to the significant difference observed around the fly kick, this significant difference is largely in relation to temporal patterning of the sub skills.

Due to the results identified above, a further analysis was completed on the separated technique. SPM results highlighted no significant differences throughout the BUP for elite and sub-elite swimmers therefore confirming the hypothesis that temporal factors contributed to the previous critical threshold being exceeded. These results are in line with Gonjo & Olstad (2021) who found that in short course swimming significant differences were observed between elite and sub-elite breaststrokers for clean swimming speed and yet no significant difference was observed at any point throughout the pull-out segment.

Gonjo & Olstad (2021) hypothesised that due to there being a positive relationship between leg kick and breaststroke free swimming velocity, a significant difference would be found with the kick in the pull-out segment, however this was not the case in either studies. The current study however performed correlations to 10 m time and discrete metrics between elite and sub-elite swimmers in addition to SPM. This additional analysis found that the kick phase max velocity was strongly correlated to 10 m time in the separated technique, with end of phase and mean velocity being found to be moderately correlated when the techniques were combined. Additionally, when broken into sub phases, elite breaststroke swimmers were found to achieve significantly higher mean velocities ($m \cdot s^{-1}$) during the breaststroke kick than sub-elite swimmers. This difference in discrete and continuous data sets might suggest that a standalone sub phase difference exists between elite and sub-elite breaststrokers however when analysed as a complete, BUP differences do not exist. Consequently, further research into the best method of comparing the BUP may be required.

When combined or separated techniques are examined, trajectories found from a push in this study are mirrored by Gonjo & Olstad (2021), who also found that sub-elite swimmers tended to show flatter vertical displacement patterns than their elite counterparts, with larger inter-individual variability also being found by sub-elite breaststrokers. Gonjo & Olstad (2021) stated that this could be due to elite swimmers changing their travelling direction at an earlier stage off the 1st glide. Additionally, the results showed a quick positive change of direction occurring around the propulsive phases of the fly kick and Pull-down. This could be due to elite swimmers utilising the propulsive phases to gain vertical displacement post the initial glide phase to maintain a high velocity and ensure they reach the surface for the breakout to be performed.

A limitation to this study could have been the exclusion of any glide time between the fly kick and the Pull-down as due to this exclusion total difference travelled and total sub phase distance did not match. Additionally, although velocity-time curves were normalised to 101 data points, temporal patterning affected the results of the SPM analysis.

7.5 Conclusion

When considering discrete metrics, elite breaststrokers have a significantly faster CoM speed in the Arm + leg recovery, yet they do not travel significantly further, therefore potentially having the ability to reduce the loss of CoM velocity through adopting less resistive positions and not amending the temporal parameters of the BUP. Additionally, elite breaststrokers can be observed to complete the BUP more efficiently with elite breaststrokers showing significantly less IVV within the BUP. Finally, through SPM the only area to identify above the critical threshold was the fly kick phase of the time-velocity curve. This however was hypothesised as a result of differing temporal patterns not solely the magnitude of CoM velocity within this phase.

8 Chapter Eight: Kinematic and kinetic analysis of the breaststroke underwater phase

8.1 Introduction

Kinematic analysis has been completed on the differences between elite and sub-elite breaststrokers' underwater phase within competition and time trials. Veiga and Roig (2016) reported that, in the 100 m breaststroke at the 2013 World Long Course Championships, faster swimmers travelled with a higher mean underwater velocity than their overall slower counterparts. Additionally, Gonjo and Olstad (2021) found that in comparison to male sub-elite swimmers, male elite swimmers, after starts and turns, produced a faster mean glide speed, in the 1st glide, during a short course 100 m time trial. Given the importance of a fast underwater velocity within both start and turn performance, researchers have stated that swimmers must optimise the underwater phase by executing a "good kinematical organisation" and sequencing of the underwater breaststroke pull-out movements in the most efficient way possible (Olstad, Wathne, & Gonjo, 2020; Sánchez, Arellano, & Cuenca-Fernández, 2021). However, this sequencing of the underwater phase is individual and coaches should employ appropriate biomechanical testing in order to ensure that the optimal timing is used for each individual's start and turn with the appropriate technique (McCabe *et al*., 2022).

A recent systematic review used an electronic search of Medline, Scopus and SPORT Discus database (Nicol et al., 2022) into stroke kinematics, temporal patterns, neuromuscular activity, pacing and kinetics in elite breaststroke free swimming and found that from 2000, 35 quality-assessed, peer-reviewed articles with in-depth selection criteria were found). However, a biomechanical analysis of the BUP has only been completed by three groups of researchers (Seifert *et al*., 2007; Seifert *et al*., 2021; Gonjo and Olstad, 2021). Seifert *et al*., 2007 used a combination of moving lateral underwater camera and multiple static lateral underwater cameras to track the swimmer throughout the underwater phase and calculate the displacement of the head. Whereas both Seifert *et al. (*2021) and Gonjo and Olstad (2021) used a static synchronised multi-camera system consisting of five underwater and five above water cameras (AIMSys Sweden AB, Lund, Sweden).

From a qualitative (visual) assessment of initiation/completion of key phases, Seifert *et al. (*2007) assessed the time spent in glide and resistive phase and Seifert *et al. (*2021) calculated the coordination profiles of their participants to establish whether swimmers glide between the dolphin kick and arm pull-out, favour continuity or even overlap those two phases. Seifert *et al. (*2007) found that all participants displayed a timing where the leg propulsion had been initiated before the Arm recovery was complete. Seifert *et al. (*2021) identified three coordination profiles where all swimmers started their dolphin kick before initiating the arm pull-out, however different timing between sub phases was present. One swimmer started the arm pull-out before the end of the dolphin kick, seven started the arm pull-out after the end of the dolphin kick, and four swimmers synchronised the beginning of the arm pull-out and the end of the dolphin kick, while two other swimmers mixed two coordination profiles among the start and the three turns.

Although Seifert *et al. (*2007) is one of a few current articles in this area, their research was completed prior to the FINA rule change in 2005 which allowed a dolphin kick to be performed once the hands had started to separate in to the Pull-down and was completed well before the 2014 rule change, allowing the dolphin kick to be performed at any point prior to the first breaststroke kick. Therefore, although this research gives some valuable insight into some aspects of the BUP it may not reflect accurately how breaststroke swimmers currently perform the BUP.

To date, no research has been completed using 3D kinematic analysis of a full-body swimmer model for the entire breaststroke underwater phase. Although previous research demonstrates that elite swimmers produce faster velocities underwater than when surface swimming and do so by a multiple of different coordination strategies, no research has examined the techniques adopted by elite swimmers in the phase of the BUP. This type of analysis is not only beneficial to understand the mechanics of how elite breaststrokers produce faster velocities but also enables the ability to further research into propulsive and drag forces surrounding the BUP. This study will therefore be the first to undertake this analysis.

Although a full kinematic analysis of the BUP has yet to be completed, such analysis has been undertaken on elements of breaststroke free swimming. Olstad *et al. (*2014) investigated a new method for identifying the distinct phases of the leg kick in the modern breaststroke technique and presented novel knee angle data with peak knee flexion being recorded between 43 – 64°. They found that two phases could not be accurately separated due to amplitudes in their participants' techniques. Therefore, further research by Olstad *et al. (*2016) simplified the kick into three phases, 1) knee extension phase – from the smallest knee angle during recovery to the first peak in knee angle during the knee extension phase; 2) knee extended phase from the end of the knee extension to the beginning of active knee flexion for Leg recovery and 3) knee flexion phase - from the end of knee extended phase until the smallest knee angle.

Within this research Olstad *et al. (*2016) completed a 3D kinematic analysis using a 3D motion capture system of the breaststroke leg-kick alongside an investigation of the muscle coordination and activation at submaximal and maximal efforts. They reported that knee flexion angle at the beginning of the extension phase decreased (knees more flexed) from 44.8° at 60% effort to 42.3° at 100% effort. Olstad *et al. (*2016) concluded that the observed increase in kick velocity, when effort levels were increased, was largely due to the greater knee flexion at the beginning of the knee extension, with swimmers' heels starting closer to the buttocks enabling them to increase the distance for their feet to travel and apply force on the water. In addition, elite swimmers were found to minimise the time spent in the knee extended phase and knee flexion phase indicating a quicker and more propulsive recovery therefore increasing momentum when swimming at 100% effort. These knee angle results are similar to Olstad *et al. (*2017) although phases of the kick were divided and defined slightly differently due to the wave/whip kick motion of the participants. Olstad *et al. (*2014) also reported that their participants exhibited a quite consistent foot slip, ranging from 300-320 mm, regardless of the kick technique used. Foot slip is defined as the backwards movement of the foot from kick initiation until forward movement is produced.

Although Olstad *et al. (*2017, 2014) obtained kinematic data on the breaststroke kick from a surface-swimming stroke cycle, the surface-swimming breaststroke kick is not dissimilar to that performed underwater within the BUP so their data may be comparable to those obtained in the current study.

Research has found that elite swimmers maintain a higher velocity than non-elite swimmers throughout the glide phases of the BUP (Gonjo and Olstad, 2021). In addition, Pease and Vennell (2010) observed that if a swimmer displays a positive body angle of attack close to the water surface, the separation of the water flow occurs earlier, at the fingertips and has a larger direct impact with the free water surface, consequently increasing wave drag and thereby total drag. However, if the swimmer is in a negative angle of attack at the same depth, the water separation flows more on the underside of the swimmer reducing the surface interaction and consequently the wave drag is not as high as a positive angle of attack. Although a larger amount of the BUP is completed underwater, the swimmer progressively moves closer to the surface of the water, therefore this research's findings could be more applicable to the 2nd glide phase.

In addition to breaststroke kick kinematics, 3D hand trajectories throughout the pull in breaststroke free-swimming have been researched by Silvatti *et al. (*2013). Their results showed asymmetries between right and left hands for both participants, highlighting that a potential propulsive difference existed between sides which could potentially lead to an uncoordinated and unstable stroke. This study highlights the importance of 3D analysis of breaststroke and the increased information that can be gained in comparison to 2D analysis. Currently there is no further research on pull phase kinematics of breaststroke swimming.

Although no data exist on hand speed in a breaststroke Pull-down, the trajectory of a butterfly arm cycle could be seen as comparable to a breaststroke Pull-down with the arms starting above the head and ending by the hips. Barbosa *et al. (*2008) reported that the horizontal velocity of the hands during the insweep and upsweep of a butterfly stroke had a significant association with horizontal swimming velocity. Thus, hand speed may be a key metric within a breaststroke Pull-down that could influence horizontal velocity and overall underwater performance.

The aims of this study are to:

1) determine the strength of association between selected kinematic variables and 10 m time in the BUP, to identify the important aspects of BUP performance;

2) Identify kinematic differences between elite breaststroke specialists and sub-elite swimmers in the BUP.

8.2 Method

For details of the equipment used, data collection, specifics surrounding the calibration of equipment, experimental protocol and data processing refer to Chapter 4: General methods section (p.55).

8.2.1 Kinematic variables

For this study, all kinematic variables were calculated from the initiation of the fly kick to the instant of breakout, defined as moment the swimmer's head breaks the surface of the water or when their arms reach the widest part of the stroke.

Kinematic variables were organised according to the BUP sub-phases previously defined chapter 6. Joint centre displacement-time histories were used to calculate the following kinematic variables:

Fly kick amplitude (m) - the maximum vertical displacement of the mean left and right foot covered during the fly kick.

Fly kick trunk incline (°) - the angle between the hip-to-shoulder and the horizontal.

Fly kick maximum foot speed ($m{\cdot}s^{-1}$) – maximum speed found of the left and right mean foot speed throughout the fly kick phase.

Fly kick mean foot speed ($m{\cdot}s^{-1}$) **–** mean foot speed of the left and right foot throughout the fly kick phase.

Pull-down Elbow Separation distance (m) **-** the largest difference in the displacement (separation distance) of the left and right lateral epicondyles of the humerus during the Pull-down.

Pull-down Wrist Separation distance (m) **-** the largest difference in the displacement (separation distance) of the left and right styloid processes of the ulna during the Pull-down.

Pull-down Fingers Separation distance (m) **-** the largest difference in the displacement (separation distance) of the left and right most distal point of the 2nd phalange (index finger) during the Pull-down.

Pull-down Max Hand speed ($m \cdot s^{-1}$) - maximum speed found of the left and right mean hand speed throughout the Pull-down phase.

Pull-down Mean Hand speed ($m \cdot s^{-1}$) - mean hand speed of the left and right hand throughout the Pull-down phase.

Pull-down Min Elbow Angle (°) – minimum three-point angle between the acromia, lateral epicondyles of the humerus and styloid process of the ulna within the Pull-down.

Pull-down Max Elbow Angle (°) - maximum three-point angle between the acromia, lateral epicondyles of the humerus and styloid process of the ulna within the Pull-down.

Pull-down hand slip (m) – y-displacement of styloid processes of the ulna marker from the initiation of Pull-down until the y-displacement reached a local mimima at the end of the Pull-down.

Recovery Min Elbow Angle (°) - minimum three-point angle between the acromia, lateral epicondyles of the humerus and styloid process of the ulna within the Arm recovery.

Recovery Elbow Separation distance (m) - the largest difference in the displacement (separation distance) of the left and right lateral epicondyles of the humerus during the Arm recovery.

Recovery Wrist Separation distance (m) - the largest difference in the displacement (separation distance) of the left and right styloid processes of the ulna during the Arm recovery.

Recovery Fingers Separation distance (m) - the largest difference in the displacement (separation distance) of the left and right most distal point of the 2^{nd} phalange (index finger) during the Arm recovery.

Recovery Max Hand speed (m·s-1) - maximum speed found of the left and right mean hand speed throughout the recovery phase.

Recovery Mean Hand speed (m·s-1) - mean hand speed of the left and right hand throughout the recovery phase.

Recovery Min Elbow Angle (°) – minimum three-point angle between the acromia, lateral epicondyles of the humerus and styloid process of the ulna within the Arm recovery.

Kick foot slip (m) - y-displacement of lateral malleolus marker from the initiation of kick until the y-displacement of the lateral malleolus marker changed from moving backwards to moving forward.

Kick Initiation Hip Flexion Angle (°) - three-point angle between the acromion, greater trochanter and lateral epicondyles of the tibia was calculated at the point of kick initiation.

Kick initiation knee angle (°) - three-point angle between the greater trochanter, lateral epicondyles of the tibia and lateral malleolus was calculated at the point of kick initiation.

Kick Initiation Knee Separation distance (m) – the difference in the displacement (separation distance of the left and right lateral epicondyles of the tibia at the initiation of the kick.

Kick Initiation Ankle Separation distance (m) - the difference in the displacement (separation distance of the left and right lateral malleolus at the initiation of the kick.

Kick Initiation Toe Separation distance (m) - the difference in the displacement (separation distance) of the left and right distal phalange of the Hallux at the initiation of the kick.

Kick Max Knee Separation distance (m) - the maximum difference in the displacement (separation distance) of the left and right lateral epicondyles of the tibia within the kick.

Kick Max Ankle Separation distance (m) - the maximum difference in the displacement (separation distance) of the left and right lateral malleolus within the kick.

Kick Max Toe Separation distance (m) - the maximum difference in the displacement (separation distance) of the left and right distal phalange of the Hallux within the kick.

Kick Max Foot speed ($m{\cdot}s^{-1}$) - maximum speed found of the left and right mean foot speed throughout the kick phase.

Kick Mean Foot speed ($m{\cdot}s^{-1}$) - mean foot speed of the left and right foot throughout the kick phase.

All variables were divided into coordination profiles for correlational analysis and further divided into elite and sub-elite participants for further analysis (separated vs overlap).

Angle of attack **(°)** – angle between the whole-body CoM velocity (resultant of y and z components) and the angle of the longitudinal axis of the body – henceforth referred to as the body orientation angle. The longitudinal axis was defined as the line of best fit (linear trendline) on a sagittal plane plot of the body segment mass centre locations (y versus z coordinates).

The linear trendline ($z = a \cdot y + b$) defining the swimmer's longitudinal axis was obtained in MS Excel. The body orientation angle was calculated from the slope (a) of the linear function.

Body orientation angle (°) = ATAN (a) · 360 / 2 π   8.1

CoM Velocity (°) =ATAN [CoM v(Y)/ CoM v(Z)]   8.2

Angle of attack (°) = Body Orientation angle (°) – CoM Velocity (°)   8.3

Additionally, 3D scanning was completed by Total Sim on four participants in a streamline body position and 2nd glide body position. These scans were then imported into Total Sim's computational fluid dynamics software (OpenFoam-v2.2x) where the total drag acting on the swimmer, at a fixed speed of 2.5 $m \cdot s^{-1}$, was computed for angles of attack ranging from -5° to +5°. A DES turbulence method was used with a Spalart-Allmarasnear wall model as the flow model throughout the CFD trials.

Each swimmer's angle of attack versus drag function was used to calculated a k-value ($k = drag / v^2$) for each angle of attack. The drag acting on the swimmers throughout their first and second glides was then estimated using the relevant k-values and instantaneous glide speeds. This was then compared to a theoretical minimum drag based on optimum angle of attack.

8.2.2 Statistical Analysis

The normality and homoscedasticity assumptions were checked respectively with Sharipo Wilks and Levene's tests. Descriptive statistics of means and standard deviations were calculated for all variables.

Shapiro–Wilk test found data both did not and did meet the required assumptions therefore Spearman rank correlation coefficients and Pearson correlation coefficients were calculated, respectively, to establish the strength of association between 10 m time and all kinematic variables. Specifically, Spearman rank correlations were completed for Total mean velocity, Pulldown minimum elbow angle, Kick initiation knee separation distance, Kick initiation ankle separation distance and Kick maximum foot velocity for the separated technique and Pulldown wrist separation distance, Pulldown minimum elbow angle, Recovery wrist separation distance, Kick average foot velocity and Kick thigh angle for the overlap technique. A correlation was considered significant if $P < .05$. A correlation was considered significant if $P < .05$. Correlations were defined as follows: weak, <.4; moderate, .4 – .6; or strong, >.6 (Mukaka, 2012).

MANOVA was used to identify the effect of skill level on all kinematic dependent variables for the separated BUP technique with only descriptive statistics being obtained for the overlap BUP technique due to a small sample. Effect sizes were calculated using partial eta squared. Pairwise comparisons were then used to identify further significant differences. In this study, $P < .05$ was considered significant.

Specifically, for angle of attack, Pearson correlation coefficients were calculated, to establish the strength of association between mean glide velocity and angle of attack. Independent t tests were completed to identify significance differences between elite and sub-elite swimmers for angle of attack.

8.3 Results

Table 8-1: Correlation coefficients between kinematic variables and 10 m time for separate and overlap BUP techniques.

	Separated technique		Overlap technique	
	Correlation Coefficient	p	Correlation Coefficient	p
Fly kick Amplitude (m)	.40	.15	-.83*	.04
Fly kick Trunk Incline (°)	.35	.27	-.50	.31
Fly kick Max Foot speed ($m{\cdot}s^{-1}$)	-.43	.21	-.76	.08
Fly kick Mean Foot speed ($m{\cdot}s^{-1}$)	-.29	.42	-.44	.38
Pull-down Elbow Separation distance (m)	-.20	.48	.31	.56
Pull-down Wrist Separation distance (m)	.23	.32	.75	.08
Pull-down Fingers Separation distance (m)	.14	.43	-.58	.23
Pull-down Max Hand speed ($m{\cdot}s^{-1}$)	-.63	.08	-.89*	.02
Pull-down Mean Hand speed ($m{\cdot}s^{-1}$)	-.77**	.01	-.88*	.02
Pull-down Min Elbow Angle (°)	-.20	.48	.09	.87
Pull-down Max Elbow Angle (°)	-.52	.06	.19	.73
Pull-down Hand Slip (m)	-.26	.32	-.55	.26
Recovery Elbow Separation distance (m)	.17	.35	-.51	.31
Recovery Wrist Separation distance (m)	.27	.23	-.03	.96
Recovery Fingers Separation distance (m)	.31	.20	.68	.14
Recovery Max Hand speed ($m{\cdot}s^{-1}$)	-.38	.20	-.69	.13
Recovery Mean Hand speed ($m{\cdot}s^{-1}$)	-.43	.12	-.71	.12
Recovery Min Elbow Angle (°)	.16	.97	.11	.84
Kick Initiation Knee Separation distance (m)	.11	.72	.27	.61
Kick Initiation Ankle Separation distance (m)	-.40	.17	.34	.51
Kick Initiation Toe Separation distance (m)	-.05	.89	.11	.84
Kick Max Knee Separation distance (m)	.18	.48	.03	.96
Kick Max Ankle Separation distance (m)	.15	.44	.10	.85
Kick Max Toe Separation distance (m)	.11	.53	-.18	.73
Kick Mean Foot speed ($m{\cdot}s^{-1}$)	-.56*	.03	-.77	.07
Kick Max Foot speed ($m{\cdot}s^{-1}$)	-.08	.80	-.99*	<.001
Kick Foot Slip (m)	-.12	.55	.77	.07
Kick Initiation Hip Flexion Angle (°)	-.60*	.02	-.43	.40
Kick Initiation Knee Angle (°)	-.01	.16	.78	.07

*. Correlation is significant at the .05 level (2-tailed).

**. Correlation is significant at the .01 level (2-tailed).

Table 8-1 shows that for both the separated technique and overlap technique Pull-down, mean hand speed (r= -.77, p= .02 and r= -.88, p= .02 respectively) is strongly negatively correlated to 10 m time. For the separated technique, mean foot speed in the kick and Kick Initiation Hip Flexion Angle were moderately negatively correlated to 10 m time ($r= -.56$, $p= .03$, $r= -.6$, $p= .02$). Fly kick amplitude ($r= -.83$, $p= .04$), Pull-down maximum hand speed ($r= -.89$, $p= .02$) and kick maximum foot speed ($r = -.99$, $p <.001$) were the only additional metrics found for the overlap technique to be strongly negatively correlated to 10 m time. No association was found between 10 m time and any other variable.

Table 8-2: Descriptive statistics including mean, range and standard deviations for 10 m time and BUP fly kick kinematic variables for Sub-elite and Elite separated technique (n=11, 4) and overlap technique (n=3, 3). MANOVA was used to identify the effect of skill level on fly kick kinematic variables for the separated technique.

Variables	SEPARATED		p	OVERLAP	
	Sub-elite (n=11)	Elite (n=4)		Sub-elite (n=3)	Elite (n=3)
Time 10 m (s)	5.92 ± 0.53	4.97 ± 0.09	.01 *	6.25 ± 0.44	5.80 ± 0.49
	(5.32 – 6.76)	(4.91 – 5.08)		(5.78 - 6.65)	(5.24 - 6.14)
Fly kick Amplitude (m)	0.78 ± 0.14	0.77 ± 0.02	.87	0.71 ± 0.20	0.82 ± 0.10
	(0.6 - .96)	(0.74 - 0.78)		(0.50 - 0.92)	(0.76 - 0.87)
Fly kick Trunk Incline (°)	23 ± 8	27 ± 6	.46	16 ± 2	20 ± 2
	(10 - 32)	(21 - 32)		(14 - 17)	(19 - 22)
Fly kick Maximum Foot speed ($m{\cdot}s^{-1}$)	3.43 ± 0.26	3.87 ± 0.02	.02 *	3.25 ± 0.62	3.29 ± 0.26
	(3.03 - 3.80)	(3.84 - 3.88)		(2.71 - 3.92)	(3.04 - 3.55)
Fly kick Mean Foot speed ($m{\cdot}s^{-1}$)	2.34 ± 0.16	2.38 ± 0.08	.66	2.28 ± 0.15	2.23 ± 0.38
	(2.12 - 2.63)	(2.29 - 2.45)		(2.11 - 2.37)	(2.20 - 2.27)

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

Table 8-3: Descriptive statistics including mean, range and standard deviations for BUP Pull-down kinematic variables for Sub-elite and Elite separated technique (n=11, 4) and overlap technique (n=3, 3). MANOVA was used to identify the effect of skill level on Pull-down kinematic variables for the separated technique.

	SEPARATED			OVERLAP	
	Sub-elite (n=11)	Elite (n=4)	p	Sub-elite (n=10)	Elite (n=4)
Pull-down Elbow Separation distance (m)	0.80 ± 0.02	0.81 ± 0.05	.56	0.78 ± 0.10	0.76 ± 0.05
	(0.77 - 0.83)	(0.76 - 0.85)	.03	(0.73 - 0.84)	(0.71 - 0.81)
Pull-down Wrist Separation distance (m)	0.91 ± 0.07	0.91 ± 0.04	.92	0.91 ± 0.17	0.83 ± 0.06
	(0.81 - 1.01)	(0.87 - 0.93)	.00	(0.81 - 1.10)	(0.78 - 0.90)
Pull-down Fingers Separation distance (m)	1.17 ± 0.09	1.14 ± 0.05	.60	1.12 ± 0.24	1.05 ± 0.08
	(1.00 - 1.28)	(1.13 - 1.22)	.03	(0.96 - 1.39)	(0.98 - 1.13)
Pull-down Max Hand speed (m)	3.13 ± 0.25	3.51 ± 0.30	.05	3.02 ± 0.25	3.12 ± 0.44
	(2.52 - 3.31)	(3.20 - 3.80)	.31	(2.85 - 3.30)	(2.80 - 3.62)
Pull-down Mean Hand speed ($m \cdot s^{-1}$)	2.37 ± 0.15	2.71 ± 0.15	.01 *	2.22 ± 0.18	2.37 ± 0.08
	(2.01 - 2.50)	(2.56 - 2.86)	.53	(2.09 - 2.43)	(2.29 - 2.45)
Pull-down Max Elbow Angle (°)	173 ± 4	176 ± 4	.30	176 ± 1	178 ± 2
	(166 - 178)	(171 - 179)	.10	(175 - 178)	(176 - 179)
Pull-down Min Elbow Angle (°)	91 ± 16	100 ± 7	.34	88 ± 33	99 ± 9
	(48 - 105)	(92 - 106)	.08	(50 - 108)	(88 - 105)
Pull-down Hand Slip (m)	0.51 ± 0.08	0.56 ± 0.10	.49	0.52 ± 0.08	0.51 ± 0.11
	(0.33 - 0.63)	(0.45 - 0.63)	.05	(0.45 - 0.61)	(0.38 - 0.58)

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

Table 8-2 highlights for the separated technique a significant difference existed between elite and sub-elite swimmers for 10 m time (p= .01, partial eta squared =.45) and fly kick maximum foot speed (p= .02, partial eta squared = .42). With elite swimmer's feet reaching 0.44 m·s-1 faster in the fly kick than sub-elite swimmers.

Due to the small sample size, no statistical analysis was completed on the overlap technique. However descriptive statistics show a large difference between elite and sub-elite swimmers for 10 m time with elite swimmers performing 0.45 s quicker than sub-elite swimmers.

Table 8-3 highlights for the separated technique a significant difference existed between elite and sub-elite swimmers Pull-down mean hand speed (*p*= .01, partial eta squared =.53) and a border-line significant difference in Pull-down maximum hand speed (*p*= .05, partial eta squared =.31) with elite swimmer's hands travelling 0.34 $m \cdot s^{-1}$ faster throughout the Pull-down than sub-elite swimmers.

Due to the small sample size, no statistical analysis was completed on the overlap technique. However descriptive statistics show a large difference between elite and sub-elite swimmers for Pull-down maximum hand speed, Pull-down minimum elbow angle, with elite swimmers showing a greater minimum elbow angle and faster maximum hand speed. These differences are similar to those found between elite and sub-elite in the separated technique.

Table 8-4: Descriptive statistics including mean, range and standard deviations for BUP Arm and leg recovery kinematic variables for Sub-elite and Elite separated technique (n=11, 4) and overlap technique (n=3, 3). MANOVA was used to identify the effect of skill level on Arm and leg recovery kinematic variables for the separated technique.

	SEPARATED			OVERLAP	
	Sub-elite (n=11)	Elite (n=4)	p	Sub-elite (n=10)	Elite (n=4)
Recovery Elbow Separation distance (m)	0.66 ± 0.05	0.64 ± 0.05	.45	0.59 ± 0.05	0.66 ± 0.03
	(0.55 - 0.72)	(0.60 - 0.69)		(0.54 - 0.63)	(0.64 - 0.69)
Recovery Wrist Separation distance (m)	0.34 ± 0.11	0.34 ± 0.18	1	0.37 ± 0.02	0.32 ± 0.08
	(0.17 - 0.51)	(0.16 - 0.51)		(0.35 - 0.38)	(0.23 - 0.37)
Recovery Fingers Separation distance (m)	0.05 ± 0.17	0.01 ± 0.26	.78	0.14 ± 0.04	0.03 ± 0.10
	(-0.25 - 0.21)	(-0.20 - 0.30)		(0.09 - 0.17)	(-0.08 - 0.11)
Recovery Max Hand speed ($m \cdot s^{-1}$)	3.06 ± 0.52	3.14 ± 0.52	.83	2.94 ± 0.70	3.30 ± 0.33
	(2.33 - 4.01)	(2.76 - 3.73)		(2.41 - 3.74)	(2.94 - 3.58)
Recovery Mean Hand speed ($m \cdot s^{-1}$)	2.32 ± 0.25	2.35 ± 0.17	.84	2.19 ± 0.50	2.46 ± 0.19
	(1.82 - 2.72)	(2.23 - 2.55)		(1.73 - 2.73)	(2.25 - 2.63)
Recovery Max Elbow Angle (°)	166 ± 6	176 ± 3	.06	171 ± 6	172 ± 2
	(151 - 175)	(173 - 180)		(165 - 178)	(170 - 173)
Recovery Min Elbow Angle (°)	52 ± 7	51 ± 4	.83	51 ± 1	52 ± 6
	(40 - 61)	(46 - 54)		(50 - 52)	(48 - 59)

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

In the Arm + leg recovery phase, no significant differences were observed between elite and sub-elite swimmers for the separated technique. Descriptive statistics for the overlap technique however do show that elite swimmers hands travel 0.27 $m \cdot s^{-1}$ faster on average throughout the recovery and produce a faster maximum hand speed by 0.36 m·s^{-1} (Table 8-4).

Table 8-5: Descriptive statistics including mean, range and standard deviations for BUP Kick kinematic variables for Sub-elite and Elite separated technique (n=11, 4) and overlap technique (n=3, 3). MANOVA was used to identify the effect of skill level on Kick kinematic variables for the separated technique.

	SEPARATED			OVERLAP	
	Sub-elite (n=11)	Elite (n=4)	p	Sub-elite (n=11)	Elite (n=4)
Kick Initiation Knee Separation distance (m)	0.65 ± 0.11	0.59 ± 0.01	.44	0.62 ± 0.02	0.49 ± 0.05
	(0.51 - 0.90)	(0.59 - 0.60)		(0.60 - 0.63)	(0.46 - 0.55)
Kick Initiation Ankle Separation distance (m)	0.47 ± 0.08	0.48 ± 0.02	.78	0.35 ± 0.12	0.44 ± 0.15
	(0.33 - 0.64)	(0.46 - 0.50)		(0.27 - 0.49)	(0.29 - 0.58)
Kick Initiation Toe Separation distance (m)	0.6 ± 0.18	0.47 ± 0.17	.29	0.35 ± 0.24	0.66 ± 0.10
	(0.36 - 0.90)	(0.30 - 0.63)		(0.08 - 0.55)	(0.55 - 0.74)
Kick Max Knee Separation distance (m)	0.67 ± 0.11	0.64 ± 0.03	.66	0.65 ± 0.01	0.57 ± 0.06
	(0.54 - 0.90)	(0.61 - 0.67)		(0.64 - 0.66)	(0.51 - 0.61)
Kick Max Ankle Separation distance (m)	0.97 ± 0.13	0.86 ± 0.08	.21	0.87 ± 0.08	0.89 ± 0.06
	(0.66 - 1.09)	(0.77 - 0.93)		(0.79 - 0.95)	(0.82 - 0.93)
Kick Max Toe Separation distance (m)	1.22 ± 0.13	1.08 ± 0.10	.05	1.11 ± 0.10	1.13 ± 0.07
	(0.92 - 1.41)	(0.97 - 1.16)		(1.00 - 1.19)	(1.06 - 1.19)
Kick Mean Foot speed (m·s^{-1})	2.97 ± 0.26	3.27 ± 0.09	.08	3.01 ± 0.25	2.9 ± 0.27
	(2.59 - 3.50)	(3.21 - 3.38)		(2.73 - 3.22)	(2.74 - 3.21)
Kick Max Foot speed (m·s^{-1})	1.98 ± 0.3	2.05 ± 0.24	.71	1.5 ± 0.33	1.7 ± 0.34
	(1.65 - 2.64)	(1.78 - 2.23)		(1.16 - 1.82)	(1.42 - 2.08)
Kick Foot Slip (m)	0.28 ± 0.04	0.31 ± 0.04	.17	0.31 ± 0.05	0.33 ± 0.05
	(0.21 - 0.32)	(0.27 - 0.34)		(0.27 - 0.36)	(0.27 - 0.37)
Kick Initiation Hip Flexion Angle (°)	102 ± 28	129 ± 5	.14	127 ± 12	105 ± 41
	(39 - 127)	(123 - 133)		(113 - 135)	(59 – 131)
Kick Initiation Knee Angle (°)	38 ± 6	39 ± 3	.61	29 ± 2	44 ± 6
	(28 - 44)	(36 - 43)		(27 - 33)	(36 - 52)

*. Significant at the .05 level (2-tailed).

**. Significant at the .01 level (2-tailed).

In the Kick phase, no significant differences were observed between elite and sub-elite swimmers for the separated technique. However, a border-line significant difference in maximum toe separation distance was observed (*p*= .05, partial eta squared = .2).

Due to the small sample size, no statistical analysis was completed on the overlap technique. However descriptive statistics show a large difference between elite and sub-elite swimmers for Kick initiation knee angle and Kick initiation toe separation distance. Displaying that elite swimmers perform the Kick phase with a larger knee angle at Kick initiation and with wider placed toes (Table 8-5).

Table 8-6: Pearson correlation coefficients between angle of attack and mean glide velocity (m·s-1) for glide 1 and 2 of the BUP.

Glide	n	Angle of attack (°)	Mean Glide Velocity ($m \cdot s^{-1}$)	Correlation Coefficient	p
1	19	-2.1 ± 3.0	1.69 ± .22	.44	.06
		(-7.2 – 5.4)	(1.25 – 2.15)		
2	19	-4.9 ± 2.5	1.61 ± .17	.38	.11
		(-9.9 to .44)	(1.29 – 1.98)		

*. Correlation is significant at the .05 level (2-tailed).

**. Correlation is significant at the .01 level (2-tailed).

Table 8-7: Descriptive statistics including mean, range and standard deviations for angle of attack and velocity of glide 1 and 2 for elite and sub-elite breaststroke swimmers.

Glide	Performance Level	n	Angle of attack (°)	Velocity ($m \cdot s^{-1}$)
1st	Elite	4	-1.3 ± 2.0 (-3.5 to 1.4)	1.83 ± 0.20 (1.57 to 2.15)
	Sub-elite	11	-2.4 ± 3.4 (-7.2 to 5.4)	1.63 ± 0.20 (1.25 to 1.94)
2nd	Elite	4	-5.1 ± 3.0 (-9.9 to -2.1)	1.70 ± 0.17 (1.47 to 1.98)
	Sub-elite	11	-4.8 ± 2.3 (-8.5 to -0.4)	1.57 ± 0.16 (1.29 to 1.84)

Table 8-6 shows that no association was found in either glide 1 or 2 (r= .44, p= .06; r= .38, p= .11, respectively)

On average, both elite and sub-elite swimmers exhibited negative angle of attacks in the first glide (-1.3 to -2.4°) and glide 2 (-5.1 to -4.8°). Specifically, in glide 2, no positive angle of attacks were observed for any of the participants (-9.9 to - 0.4°) (Table 8-7).

Table 8-8: Mean angle of attack, mean velocity, mean calculated drag, mean optimal drag and percentage difference between optimal and calculated drag for four participants in glide 1 and 2 of the BUP.

Glide	Participant	Angle of attack (°)	Mean Glide Velocity ($m \cdot s^{-1}$)	Calculated Drag (N)	Optimal Drag (N)	% Difference (%)
1	1	1.4	2.15	67.9	66.7	1.92
	2	-1.8	1.57	36.7	36.7	2.31
	3	-3.5	1.80	42.5	42.5	2.39
	4	-7.2	1.25	29.8	22.2	34.38
2	1	-2.7	1.98	55.9	55.4	0.88
	2	-5.6	1.61	32.6	33.8	-3.70
	3	-2.1	1.65	43.2	41.2	5.03
	4	-7.8	1.67	50.2	32	37.78

The participant with the smallest angle of attack related to the smallest % difference between calculated drag and optimal drag. This differed in glide 2 with participant 2's angle of attack being found to show a smaller drag value than that calculated for their mean drag (Table 8-8).

8.4 Discussion

The first aim of this study was to determine the strength of association between selected kinematic variables and 10 m time in the BUP, to highlight the importance of key metrics in BUP performance. The second aim was to identify kinematic differences between elite breaststroke specialists and sub-elite swimmers in the BUP.

The main findings were that for both the separated technique and overlap technique, Pull-down mean hand speed was strongly negatively correlated to 10 m time. This shows that, irrespective of technique, swimmers must attempt to increase the mean velocity of their hands throughout the Pull-down. These findings are in line with Koga *et al. (*2022) who found that in freestyle swimming mean swimming velocity was also positively correlated with hand speed (r = .881) and propulsive force (r = .751) with Tsunokawa, Mankyu and Ogita (2019) stating an exponential increase in propulsive force, with the increase in mean swimming velocity accrued through an increase in hand speed.

This finding was further supported by the significant difference found between elite and sub-elite swimmers for Pull-down mean hand speed and a near significant difference in Pull-down maximum hand speed. Elite swimmers' hands travelled 0.34 m·s-1 faster throughout the Pull-down than those of the sub-elite swimmers. Although no research has previously been completed on hand speed in a breaststroke Pull-down, Barbosa *et al. (*2008) found that the horizontal speed of the hands within the insweep and upsweep of a butterfly stroke had a significant association with overall swimming speed. Hand speed is clearly a key metric within a Pull-down to increase horizontal velocity and overall underwater performance in the BUP.

When techniques were combined, the separation distance of the elbows at the widest point of the pull was similar between the elite and sub-elite sample. However, the wrists and fingertips of the sub-elite swimmers were wider at this point, indicating that the elite sample kept their wrists and fingertips more in vertical alignment with their elbows (Sub elite elbow separation distance= 0.79 m, Elite elbow separation distance = 0.79 m; Sub elite wrist separation distance= 0.91 m, Elite wrist separation distance = 0.87 m; Sub elite finger separation distance= 1.15 m, Elite finger separation distance = 1.1 m). It could be speculated that this arm position potentially gave the elite sample a greater propulsive catch and pull phase of the Pull-down. The catch is determined as hand entry into the water to the beginning of the backward movement and the pull phase as the backward movement of the hands to the vertical plane of the shoulders (Seifert *et al*., 2008). It is identified in these phases that an increase in angular velocity can occur due to movement around the elbow joint accelerating the hand and forearm. The correct bending of the elbow to the vertical line involves less torque to create an effective pulling force than without bending the elbows (Vorontsov and Rumyantsev, 2000).

In addition to Pull-down metrics, mean foot speed in the Kick and Kick initiation hip flexion angle were found to be moderately negatively correlated to 10 m time for the separated technique. Highlighting that a higher foot speed in the Kick and larger hip extension at kick initiation is beneficial to achieve a quicker 10 m time.

Within breaststroke free swimming, Tsunokawa *et al. (*2015) found that the primary propulsive action is the leg kick, that there is a positive relationship between the leg propulsive impulse and the breaststroke swimming velocity and that elite swimmers do possess a higher kick impulse and overall Kick velocity than sub-elite swimmers. Although kick impulse was not calculated within this study, elite breaststrokers are likely to have achieved this higher impulse by their higher mean and maximum foot speeds. Propulsive force from the swimmer's propelling surfaces, e.g., hands and feet is proportional to the area of the hand/foot and speed of the propelling surface squared (Tsunokawa *etal*., 2018). Thus, even a small difference in foot speeds between the elite and sub-elite samples could translate to a large difference in propulsive force from the kick.

Although a negative correlation of higher foot speed to 10 m time was identified no significant difference between groups was noted. Those who did display higher foot speeds however did display less lateral knee separation at the initiation and widest part of the kick, compared to others. The ankle separation distance at Kick initiation in this study of 0.35 - 0.48 m are narrower than those reported by Sanders *et al. (*2015) for an international female breaststroker. In their case study, the ankle displacement from the centre line ranged between 0.3 and 0.45 m, consequently equalling an ankle separation of .75 m. This larger ankle width at Kick initiation was also observed by Kippenhan (2001) who noted that the foot position at the initiation of the kick was larger for higher level swimmers than less able swimmers (Kippenhan, 2001). This conflict with the findings of the current study is largely due to Sanders *et al. (*2015) and Kippenhan (2001) research focusing on the breaststroke kick within free swimming and isolated kick in comparison to the BUP. This stating that breaststroke swimmers displaying narrower ankle widths within the BUP.

Kippenhan (2001) did however identify that the less skilled the breaststroke swimmer, the greater the outward travel of the feet, resulting in a wider ankle separation throughout the 1st propulsive phase of the kick. The more skilled breaststroke swimmers displayed a greater overall downward and backward movements of the ankle joints consequently maintaining much narrower joint separation distance.

A general coaching consensus is that at the initiation of the kick, the hip flexion should be kept to a minimum to prevent the knees travelling under the body and the thighs presenting an unnecessarily high frontal area to the water, increasing drag before the most propulsive phase of the BUP (Maglischo, 2003). This study found that, although not significant, elite swimmers initiated their kick from a more extended hip position by 27.2° than sub-elite swimmers.

Foot slip was calculated for the BUP kick due to Strzała *et al. (*2012) finding that during breaststroke free swimming, foot slip was negatively correlated to a greater horizontal hip displacement. However, in agreement with Olstad *et al. (*2014), foot slip was not found to correlate with a performance measure (time to 10 m in the current study) or significantly differ between elite and sub-elite swimmers. Foot slip measures in the current study (0.21 - 0.37 m) are similar to those presented by Olstad *et al. (*0.30 - .32 m).

In this study, Kick initiation knee angle was not correlated with 10 m time or significantly different between the elite and sub-elite swimmers. Olstad *et al. (*2014) concluded that improvements in kick cycle velocity were largely due to a change in knee flexion at the beginning of the knee extension. When the swimmers' heels began closer to the buttocks, this enabling them to create a further distance for their feet to travel and apply force to the water. Their Kick initiation knee angles of 44.8 – 42.3° are similar to those of the current study sub-elite sample for the overlap technique, however the elite swimmers displayed larger flexion angles than those of Olstad *et al. (*2014). For the separated technique knee angle at kick initiation, both elite and sub-elite swimmers initiated the kick from a more flexed knee position than swimmers in Olstad *et al. (*2014) study, with up to a 6.8° difference.

When considering the fly kick within the BUP, although no correlation was found between fly kick maximum foot speed and 10 m time, a significant difference was found for the separated technique between elite and sub-elite swimmers (p= .02, effect size = .42). Elite swimmer's feet were found to travel 0.44 m·s^{-1} faster in the fly kick than sub-elite swimmers.

This is in aligns with multiple fly kicking studies (Atkison *et al*., 2014; Higgs, Pease and Sanders 2017) and identified in a recent systematic review as one of the kinematic variables which is a greatest predictor of high underwater undulatory swimming velocity (West *et al.*, 2022). Higgs, Pease and Sanders (2017) stated that peak vertical toe velocity explained for 72.3% of variance in underwater undulatory swimming (fly kicking) with Atkison *et al. (*2014) also finding peak vertical toe velocity to strongly correlate to performance for both the upbeat and downbeat phases and elite swimmers' foot speed being significantly larger than their sub-elite counterparts. Atkinson *et al. (*2014) also identified that peak vertical toe velocities are more important than mean vertical toe velocities for UDK propulsion which aligns with the standalone breaststroke fly kick in this study.

8.4.1.1 8.4.1 Angle of attack

No association was found between angle of attack and speed in either glide 1 or 2, yet a trend was visible for glide 1, with elite swimmers displaying the smallest angle of attack and performing the largest speed. However, this was not observed for glide 2. Results show that elite swimmers displaying the largest angle of attack, yet still perform the greatest speed. This result is contradictory to previous research which states that minimising the angle of attack would reduce drag consequently reducing the speed maintained throughout the phase (Bixler, Pease and Fairhurst, 2007).

Potentially in the second glide, elite swimmers may be more superior in coordinating limbs into a well organised streamline body orientation and shape whilst ascending to the surface in an initially lower drag position consequently having the ability to maintain a higher speed irrelevant of angle of attack. This is in agreement with Naemi *et al*. (2012) who suggested that shape characteristics and appropriate postural angles contribute to a higher gliding efficiency.

The results in this study identified angle of attacks of up to -9.9° that would increase drag significantly greater than previously found (Bixler, Pease and Fairhurst, 2007). Due to these large angles of attack being found it could be recommended that further CFD research in to the effects of angle of attack on drag, should include much larger ranges of pitch (-4 to +4°; Pease and Vennell, 2010).

Although a small group of athletes were reviewed, glide 1 displayed the smallest angle of attack which was found to relate to the smallest percentage difference between calculated drag and optimal drag. 3 participants displayed angle of attacks of between –3.5 to 1.4° which identified between 1.9 - 2.4% difference between optimal and calculated drag. These results are similar to research by Bixler, Pease and Fairhurst (2007) who stated that increases in angles of attack of between 3 to -4.5° could increase drag by 2.3 – 2.4%, respectively. This differed in glide 2 with participant 2's angle of attack being found to show a smaller drag value than that calculated for their mean drag. A potential reason could be due to the CFD 3D body scans being taken at a different time point to when the angle of attack data was collected and consequently the surface area of the swimmer and consequent shape characteristics could have differed between testing sessions (Naemi *et al*., 2012). Additionally, due to the swimmer not maintaining a constant velocity throughout the glide in the pool conditions, the decelerating will affect the flow conditions and consequently impact the drag calculated (REF). Further research should ensure that body scans and in-water testing are completed within a short space of time.

The largest angle of attack in glide 1 of -7.21°, resulted in the largest percentage difference between optimal and calculated drag (34.4%). This same participant also displayed the largest angle of attack within glide 2 (-7.8°) which again resulted in the largest percentage difference between optimal and calculated drag (37.8%).

8.5 Conclusion

The aims of this study were to determine the strength of association between selected kinematic variables and 10 m time in the BUP, to identify the important aspects of BUP performance and to identify kinematic differences between elite breaststroke specialists and sub-elite swimmers in the BUP. Pull-down mean hand speed was the sole variable found to be strongly negatively correlated to 10 m time for both techniques. It was also found to be significantly different between elite and sub-elite samples, identifying Pull-down mean hand speed as a key determinant to BUP performance with swimmers requiring to produce high mean hand velocities throughout the Pull-down. Although no significant difference between samples were found for kick maximum foot speed and kick mean foot speed, they were found to be associated with 10 m performance for the separated and overlap techniques respectively. This highlights that, concurring with free-swimming research, the kick has a high contribution to 10 m time performance and overall BUP performance.

Additionally, kick initiation hip flexion angle and fly kick maximum foot speed are also metrics that should be considered in relation to BUP performance.

10 Chapter Ten: General conclusions, limitations, practical applications and future studies

10.1 General Conclusions

There are two main aims of this thesis: 1) to identify the critical physical and technical factors affecting intra cyclic speed fluctuations in the underwater phase of breaststroke and 2) to determine, through the use of case studies, whether an intervention using established critical determinants of a BUP can improve performance.

Chapter 3 identified that, irrelevant of gender or event, GB breaststrokers have a large scope for improvement in starts and turns in comparison to their international counterparts. Through a greater investigation into the determining factor of the BUP, large improvements could be made which could be the determining factor between winning an Olympic gold medal and not. The men's 50 m breaststroke was the sole event where GB swimmers' free-swimming was on average faster than non-GB swimmers. However, in the men's 100 m the percentage difference for the free swim was less than for starts/turns, demonstrating that GB swimmers in these events are further away from their international counterparts in start and turn elements than the free swimming one. Opposing results were notes for GB women in the 200 m event as they were found to be better at starts and turns than their international competitors. In addition, study 1 showed that start and turn time were correlated to race time for both male and female multiple events.

Chapter 5 compared the CoM speed obtained through 3D video analysis to that of the speed derived from a fixed point of the hip and the speed reel system speed output for the breaststroke underwater phase. It was found that although CoM, mid-hip and speed reel speed time curves all display similar patterns, differences were present between speed collection methods. Specifically, the speed reel over and underestimates peak and minimal speeds, respectively. Therefore, although it was deemed that the speed reel was still a sufficient tool for collecting speed data in place of mid-hip or CoM data throughout the whole BUP, it was even more the case when solely isolating the glide phase. It is recommended that the speed reel output should be interpreted with caution with minimum and maximum speeds not being reported as a good representation of swimmer speed. However, glide or total BUP mean speed could be used as a good tool to monitor progression throughout technical interventions.

Chapter 6 examined temporal characteristics of the BUP. The study showed that the majority of swimmers performed the separated technique rather than the overlap technique. It also established that when comparing the BUP temporal phases following a dive entry and a wall push-off, a significant difference was found for the fly kick preparation phase. Therefore, to consolidate technical changes breaststroke swimmers must focus on performing their underwater phases across both starts and turn to enable the swimmers to perform their underwater phases to the best of their ability when performing both skills. Secondly, this study found that when focusing on the separated technique, the time spent in the Fly kick preparation phase and Kick phase were negatively and positively correlated to 10 m time respectively and when broken down into individual phases, the elite sample spent a significantly longer duration and percentage in the Arm recovery and in the time between the arm to Leg recovery. This recognising that the amount of time spent in these phases may not contribute to a slower BUP as hypothesised if the legs are in the least resistive (straight) position throughout a larger percentage of the Arm recovery.

In chapter 7, when techniques were examined together or solely the separated techniques are looked in to, trajectories showed that sub-elite swimmers tended to show flatter vertical displacement patters than their elite counterparts with larger inter-individual variability also being found by sub-elite breaststrokers. Additionally, counteracting the negative direction from the 1st glide, this current study shows a quick positive change of direction occurring around the propulsive phases of the fly kick and Pull-down. However, when comparing elite and sub-elite breaststrokers who complete the overlap technique this contradicts previous results finding that elite swimmers who perform the overlap technique show a flatter trajectory. It was also found that when looking into discrete metrics, elite breaststrokers have a significantly faster velocity in the Arm + leg recovery. Therefore, elite breaststroke swimmers potentially have the ability to reduce the loss of CoM velocity by adopting less resistive positions but not necessarily by amending the temporal parameters of the BUP. Additionally, elite swimmers display a higher mean velocity within the Pull-down, 2nd glide and kick, identifying the ability to maintain a high velocity throughout these phases as a key determinant of the BUP. Additionally, strong correlations to 10 m time were found for total BUP mean velocity, Fly kick preparation phase minimum velocity, Pull-down and glide 2 start and end velocities, maximum Pull-down velocity, mean Arm + leg recovery velocity and max kick velocity. Breakout distance, Fly kick preparation phase distance gained, Arm + leg recovery end of phase distance and Arm + leg recovery minimum velocity distance were all also found to be strongly correlated to 10 m time.

Chapter 8 identified Pull-down mean hand speed as the sole variable found to be strongly negatively correlated to 10 m time for both techniques. It was also found to be significantly different between elite and sub-elite samples, identifying Pull-down mean hand speed as a key determinant to BUP performance. Although no significantly difference between samples, kick maximum foot speed and kick meant foot speed were found to be negatively correlated with 10 m performance for the separated and overlap techniques, highlighting (in agreement with free-swimming research), that the kick has a high contribution to 10 m time performance and overall BUP performance. Additionally, kick initiation hip flexion angle and fly kick maximum foot speed are also metrics that should be considered in relation to BUP performance.

Chapter 9 showed that over a 5-year period the athlete in this case study reduced their start time by 0.26 s. This was achieved through multiple interventions; however, the largest detectible change was found following an intervention focused on producing a rear weighted start. Changes to wedge position, fly kick amplitude and flight trajectory also led to detectable changes in start time being noted. The body mass and strength of the swimmer could have contributed to some reduction in time however the reductions in start time were maintained irrelevant of changes in body mass.

10.2 Practical Applications

It was identified that within both elite and sub-elite groups, two techniques were performed (separated and overlap) with similar mean times to 10 m, indicating that the sequencing of the underwater phase used by a swimmer is largely individual and coaches should conduct simple testing with stopwatches in order to ensure that the fastest technique is being used for each individual's start and turn (McCabe *et al*., 2022).

10.2.1 Fly kick phase

Based on the key determinants found in this thesis, it is recommended that when performing a fly kick as part of the BUP, maximum foot velocity should be a key focus. Consequently, swimmers should aim to move their feet as fast as possible, working on both speed in the downbeat and upbeat of the fly kick, potentially working technically on the organisation of limbs to facilitate this.

Additionally, although it was hypothesised that elite swimmers may have a smaller trunk incline and spend less time in the Fly kick preparation phase than sub-elite swimmers, this was not found. Therefore, if the swimmer has the ability to produce sufficient propulsion to counteract the drag acting on the body in the Fly kick preparation phase and produces a good horizontal displacement from the phase, then amplitude of the upper body and/or time spent in the Fly kick preparation phase is not necessarily performance-limiting. The swimmer could produce the large propulsion required via foot speed through the fly kick down and upbeat or potentially performing the fly kick with a smaller trunk incline angle, increasing the alignment of the upper body in the appropriate direction.

10.2.2 Pull-down phase

Key determining factors of 10 m time performance for the Pull-down were found to be all CoM start, end and mean speeds throughout the phase. Therefore, it is important to maintain a high velocity prior to the Pull-down and to maintain a high velocity throughout. This maintenance of a high mean velocity throughout the phase was found to be key differing variable between elite and sub-elite swimmers.

It was identified that to achieve a high mean speed and time to 10 m, mean and maximum hand velocity must be increased during Pull-down. It was speculated that this could be completed by swimmers positioning the fingers and wrists vertically in line with the elbow, potentially gaining a greater catch and propulsive phase.

10.2.3 Arm and leg recovery phase

Specifically focusing on the Arm + leg recovery it was found that the time spent in this phase was not correlated to 10 m time performance however elite swimmers spent a significantly longer duration and percentage in the Arm recovery and in the time between the arm to Leg recovery. This recognises that the amount of time spent in these phases may not contribute to a slower BUP as hypothesised if the legs are in the least resistive (straight) position throughout a larger percentage of the Arm recovery. Therefore, it is recommended that although this phase is considered the most resistive phase of the BUP (Seifert *et al.*, 2007), it may not be advantageous to focus on limiting the time spent in this phase as previously thought. Instead, the focus might be on the timing of the negative superposition, ensuring the legs are in the least resistive (straight) position throughout a larger percentage of the Arm recovery. By implementing this, swimmers should be able to maintain a high velocity and travel distance throughout this phase, which was found to contribute to performance.

In addition, although not significant, elite swimmers initiated their kick from a more extended hip position than sub-elite swimmers preventing their knees travelling under the body and the thighs presenting an unnecessarily high frontal area to the water and increasing drag before the most propulsive phase of the BUP. It is therefore recommended that swimmers should maintain a more extended hip angle at the kick initiation to achieve a less resistive position at the end of Leg recovery, potentially reducing the drag acting on the body in the Leg recovery and consequently reducing the loss of velocity into the kick.

10.2.4 Kick phase

The kick is the most propulsive phase within the BUP with time spent in the phase and maximum kick speed being strongly correlated to 10 m time. It is recommended that to fully exploit this phase, faster swimmers spend less time in the kick phase than their slower counterparts. This is achieved by elite swimmers displaying a higher mean resultant foot speed and consequently a higher mean speed throughout the phase.

10.3 Limitations

There are a number of limitations to this thesis and the studies that comprise it. These limitations have influenced the interpretation of the research results and in some instances, limited the ability to generalise the results to the larger population. The small sample size included in this thesis causes a large number of statistical tests to be under-powered which limits the ability to draw general conclusions from the work in the thesis. This was due to a number of unanticipated challenges that emerged during the study thus affecting the design of the studies and of the overall thesis.

The first specific limitation to this thesis was the necessity to sub-divide the participant cohort into two groups – the separated and overlap technique groups for some analyses. This reduced sample size for some comparisons, preventing the use of statistical analysis of one technique and reducing the statistical power of the other. Although it was found by this thesis that the separated technique is more popular among the elite and sub-elite sample, both techniques are still performed and were found to be significantly different within the temporal patterning and completion of the BUP. Further research is still required into both techniques due to the individual nature of elite performance.

Additionally, the requirement to pool male and female participants together for some analyses was identified as a limitation to the thesis. This was due to the participant sample becoming too small when divided into technique and gender groups to obtain any valid assumptions. The justification of pooling genders for results to be obtained was that in both elite and sub-elite samples, 29-31% of both samples were female therefore a gender bias was mitigated.

A further limitation of the thesis, excluding the case study, was that all correlation and significant difference assumptions were based on inter-swimmer comparisons. At the initiation of the thesis it was hoped that the research would be longitudinal in nature to draw more intra-swimmer comparisons however due to limited pool time and access to participants it was not possible. Therefore, further research should focus on what kinematic variables have changed specifically for an individual swimmer over a 2-year or longer period that could provide reasoning for each individual's improvement (or lack of) in BUP performance.

A limitation of the case study was the irregularity of data collected. Due to the data being collected over a 5-year period prior to the commencement of this thesis, the data collection was not consistent. Additionally, due to the retrospective nature of the study limited training data in the water was available and if present would have further supported the case study.

10.4 Suggestions for further research

Based on the phases of the BUP that were found to be associated with 10 m time, a more in-depth analysis of joint kinematics should be completed to provide greater insight into the propulsive movements of the upper and lower limbs.

A further study could be completed to understand the level of net gain, if any, from the fly kick. The ability to quantify the performance benefit of the fly kick would further develop the understanding the BUP performance.

Although a preliminary analysis of body angle of attack and its relationship to drag during the two BUP glide phases was included in this thesis, this was limited to four swimmers. Further research could explore the relationship between angle of attack, drag and glide performance for a broader range of swimmers. The impact that angle of attack has on the swimmer's glide trajectory, due to the lift component, is also a topic worthy of further work.

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Appendix

Appendix one – Ethical Approval

Manchester Metropolitan University

26/09/2018

Project Title: The critical physical and technical factors affecting intra cyclic speed fluctuations in the underwater phase of breaststroke

EthOS Reference Number: 0396

Ethical Opinion

Dear Emma Louise Mosscrop,

The above application was reviewed by the MMU Cheshire Research Ethics and Governance Committee and, on the 26/09/2018, was given a favourable ethical opinion. The approval is in place until 01/09/2021 .

Conditions of favourable ethical opinion

Application Documents

Document Type	File Name	Date	Version
Project Proposal	RD1 Proposal	01/01/2018	1
Consent Form	Consent Form	06/03/2018	1
Information Sheet	Participant Information Sheet	06/03/2018	1
Additional Documentation	Signed risk assessments	08/08/2018	2

The MMU Cheshire Research Ethics and Governance Committee favourable ethical opinion is granted with the following conditions

Adherence to Manchester Metropolitan University's Policies and procedures

This ethical approval is conditional on adherence to Manchester Metropolitan University's Policies, Procedures, guidance and Standard Operating procedures. These can be found on the Manchester Metropolitan University Research Ethics and Governance webpages.

Appendix 2 - Participant Information Sheet

Participant Information Sheet

Emma Mosscrop

PhD

Valetine Building

Exercise and Sports Science

Manchester Metropolitan University

Tel: 07837481645

‘The critical physical and technical factors affecting intra cyclic speed fluctuations in the underwater phase of breaststroke’

Invitation paragraph

I would like to invite you to take part in a research study. Before you agree/disagree to take part, I would like to explain why the research is being completed and what is required of yourself. Please take time to read the following information carefully to help you fully understand. Please ask any questions if you do not understand something or would like more information before deciding whether to take part in this study.

What is the purpose of the study?

The purpose of this study is to further inform on how we collect breaststroke underwater phase data and to identify areas of largest development for individual swimmers to improve performance.

Why have I been invited to take part in the study?

You have been invited to take part in this research as you are an elite swimmer from the National Performance Centres, a highly trained swimmer from a club or a University swimmer whose main strokes are breaststroke or the 200m/400m individual medley (IM).

Do I have to take part?

It is your choice to decide if you want to take part. We will explain the study and give you time to read through this information sheet and ask any questions you have. After this we will ask you to sign a consent form to show that you have agreed/disagreed to take part in the study. If you have agreed to take part you are free to withdraw at any time, without giving a reason. If you choose to withdraw no changes to your regular sports science support will occur.

What will happen to me if I take part?

The research will be completed over four years where you may be required to complete up to six organised data collection sessions which will vary in length. During the data collection sessions, video, speed and accelerometer data may be recorded when completing the breaststroke underwater phase. Identification markers may be stuck to the surface of the skin or draw on with a permanent marker.

Expenses and payments?

No expenses or payments will be made for participating in this research.

What will I have to do?

You will be required to attend up to six organised data collection sessions which will vary in length. During the data collection sessions you will be required to complete multiple trials of the breaststroke underwater phase.

What are the possible disadvantages and risks of taking part?

The possible risks of taking part in this study are the risk of Musculoskeletal injuries to the participant when completing the whole or part of the breaststroke underwater phase. However, this risk will be reduced by completing a full warm up before completing any task for this study.

What are the possible benefits of taking part?

We cannot promise the study will help you specifically however it will help to increase our understanding and knowledge of the breaststroke underwater phase and help to improve the performance of this skill.

What if there is a problem?

If you have a concern about any aspect of this study, please contact the researcher (Emma Mosscrop – Tel: 07837481645) who will try and answer any questions and/or resolve the concern. If you still have a concern and want to complain formally please contact the research supervisors (Dr Carl Payton – email: c.payton@mmu.ac.uk, Mr Oliver Logan – email: oliver.logan@swimming.org or the Research Ethics and Governance Managers (ethics@mmu.ac.uk).

Will my taking part in the study be kept confidential?

All information and data collected throughout this research will be kept anonymous and be given a participant identifier, known only to the researcher and supervisory team. The data and a master list identifying the research codes will be stored on a password protected computer which the researcher and supervisory team has access to. In the case that the data needs transferring to another computer or a copy made for a supervisor, the data will be kept on an encrypted hard drive. The researcher and supervisory team will be the only authorised persons to view the data unless consent has been given by the participant.

What will happen if I don't carry on with the study?

If you withdraw from the study we will keep and use all of your data collected up to the point of your withdrawal. No more data will be collected after withdrawal.

What will happen to the results of the research study?

All results will be published at the end of the study. These results will be anonymous you will not be able to be identified in any publication. The results will be shown to yourself your coach and members of the sports science and sports medicine team if your consent is given.

Who is organising or sponsoring the research?

This research is organised and sponsored by British Swimming and Manchester Metropolitan University.

Further information and contact details:

Contact details of lead researcher:

Emma Mosscrop – 07837481645 (emma.l.mosscrop@stu.mmu.ac.uk)

Contact details of supervisory team:

Dr Carl Payton – email: c.payton@mmu.ac.uk

Mr Oliver Logan – email: oliver.logan@swimming.org

Contact details of complaints procedure:

Research Ethics and Governance Managers - ethics@mmu.ac.uk

Appendix 3

Table A: Descriptive statistics including mean, range and standard deviations for duration of time spent in the BUP sub phase for Sub-elite and Elite separated technique (n=11, 4)

	Performance Level	N	Time spent in phase ± Std. Deviation (Min-max)	Sig.
10 m Time	Elite	4	5.01 ± 0.11 (4.91 – 5.12)	
	Sub-elite	11	5.97 ± 0.54 (5.32 – 5.80)	.005*
1st Glide	Elite	4	1.10 ± 0.20 (0.90 – 1.36)	
	Sub-elite	11	1.13 ± 0.37 (0.82 - 1.78)	.88
Fly kick preparation	Elite	4	0.20 ± 0.06 (0.12 - 0.24)	
	Sub-elite	11	0.14 ± 0.05 (0.06 - 0.22)	.08
Fly kick recovery	Elite	4	0.33 ± 0.38 (0.30 - 0.38)	
	Sub-elite	11	0.34 ± 0.05 (0.26 - 0.40)	.77
Fly kick downbeat	Elite	4	0.23 ± 0.01 (0.22 - 0.24)	
	Sub-elite	11	0.26 ± 0.05 (0.20 - 0.36)	.67
Fly kick upbeat	Elite	4	0.34 ± 0.10 (0.22 - 0.44)	
	Sub-elite	11	0.25 ± 0.08 (0.14 - 0.38)	.26
Full fly kick	Elite	4	1.09 ± 0.12 (0.94 - 1.20)	
	Sub-elite	11	0.98 ± 0.11 (0.82 - 1.18)	.19
Pull-down	Elite	4	0.80 ± 0.17 (0.66 - 1.04)	

	Sub-elite	11	0.77 ± 0.11 (0.64 - 0.94)	.78
2nd Glide	Elite	4	0.63 ± 0.24 (0.38 - 0.86)	
	Sub-elite	11	0.81 ± 0.35 (0.32 - 1.34)	.38
Arm recovery	Elite	4	1.18 ± 0.08 (1.06 - 1.22)	
	Sub-elite	11	1.00 ± 0.12 (0.84 - 1.16)	.03*
Leg recovery	Elite	4	0.67 ± 0.06 (0.60 - 0.74)	
	Sub-elite	11	0.63 ± 0.12 (0.46 - 0.78)	.58
Arm + leg recovery	Elite	4	1.18 ± 0.08 (1.06 - 1.22)	
	Sub-elite	11	0.97 ± 0.16 (0.74 - 1.16)	.03*
Kick	Elite	4	0.41 ± 0.03 (0.38 - 0.46)	
	Sub-elite	11	0.46 ± 0.05 (0.40 - 0.54)	.11
Glide in 1st stroke	Elite	4	-0.07 ± 0.15 (-0.28 - 0.08)	
	Sub-elite	11	0.04 ± 0.15 (-0.16 - 0.24)	.26
Arm to Leg recovery	Elite	4	0.42 ± 0.09 (0.34 - 0.52)	
	Sub-elite	11	0.23 ± 0.11 (0.04 - 0.36)	.01*

Table B: Descriptive statistics including mean, range and standard deviations for duration of time spent in the BUP sub phase for Sub-elite and Elite overlap technique (n=11, 4)

Phase	Performance Level	N	Time spent in phase ± Std. Deviation (Min-max)
10 m Time	Elite	4	5.81 ± 0.49 (5.24 – 6.14)
	Sub-elite	11	6.05 ± 0.53 (5.46 – 6.65)
1st Glide	Elite	4	1.31 ± 0.27 (1.08 – 1.60)
	Sub-elite	11	1.42 ± 0.11 (1.28 - 1.52)
Fly kick preparation	Elite	4	0.11 ± 0.12 (0.00 - 0.24)
	Sub-elite	11	0.03 ± 0.05 (0.00 - 0.10)
Fly kick recovery	Elite	4	0.33 ± 0.01 (0.32 - 0.34)
	Sub-elite	11	0.29 ± 0.10 (0.22 - 0.44)
Fly kick downbeat	Elite	4	0.24 ± 0.02 (0.22 - 0.26)
	Sub-elite	11	0.22 ± 0.02 (0.20 - 0.24)
Fly kick upbeat	Elite	4	0.35 ± 0.18 (0.18 - 0.56)
	Sub-elite	11	0.21 ± 0.12 (0.06 - 0.36)
Full fly kick	Elite	4	1.03 ± 0.08 (0.98 – 1.12)
	Sub-elite	11	0.75 ± 0.27 (0.52 – 1.14)
Pull-down	Elite	4	0.74 ± 0.04 (0.72 – 0.78)
	Sub-elite	11	0.80 ± 0.13 (0.62 - 0.92)
2nd Glide	Elite	4	0.65 ± 0.17

			(0.54 - 0.84)
	Sub-elite	11	1.11 ± 0.10 (0.86 – 1.20)
Arm recovery	Elite	4	0.99 ± 0.04 (0.94 - 1.02)
	Sub-elite	11	1.10 ± 0.24 (0.82 - 1.38)
Leg recovery	Elite	4	0.70 ± 0.09 (0.60 - 0.76)
	Sub-elite	11	0.63 ± 0.06 (0.56 - 0.70)
Arm + leg recovery	Elite	4	0.99 ± 0.04 (0.94 – 1.02)
	Sub-elite	11	1.07 ± 0.29 (0.82 – 1.48)
Kick	Elite	4	0.53 ± 0.04 (0.38 – 0.46)
	Sub-elite	11	0.48 ± 0.04 (0.42 - 0.52)
Glide in 1st stroke	Elite	4	0.19 ± 0.15 (0.02 - 0.32)
	Sub-elite	11	0.27 ± 0.52 (0.00 – 0.26)

Table C: Start Time (s) and Difference in start time (s) for the participant between each competition in date order at major competitions including Olympic Games, World Championships, European Championships, Commonwealth Games and British Championships between 2016 and 2021.

Date	Competition	Start Time (s)	Difference in start time (s) between each competition in date order
07/08/2016	Olympic Games 2016	6.60	
18/04/2017	British Championships 2017	6.88	0.28
24/07/2017	World Championships 2017	6.40	-0.48
03/03/2018	British Championships 2018	6.63	0.23
07/04/2018	Commonwealth Games 2018	6.52	-0.11
04/08/2018	European Championships 2018	6.54	0.02
16/04/2019	British Championships 2019	6.32	-0.22
22/07/2019	World Championships 2019	6.4	0.08
14/04/2021	British Championships 2021	6.44	0.04
18/05/2021	European Championships 2021	6.4	-0.04
26/07/2021	Olympic Games 2021	6.34	-0.06

Appendix 4

CMJ Test protocol completed by the British Swimming Strength and Conditioning department. Firstly the platform is zeroed before each athlete steps on to the platform to minimise the drift of the force transducers. The athlete stands motionless with their hands on their hips in the centre of the platform for the first 3 s of data capture. The athlete then performs a CMJ. Maintaining hands on their hips the athlete flexes their knees to approximately 90°. They then reverse direction without pause and attempt to gain maximum height before landing back on the platform.