# Factors affecting the underwater phase of the swimming start


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This thesis is dedicated to the most amazing and brave boy I have ever met.

My 2nd Cousin

**Nicholas Chen**

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*Thank you for inspiring me to fight through this.*

**Abstract**

The start in swimming is crucial to performance in competition. Following the introduction of the Omega OSB11 block in 2010 saw the evolution of the kick-start, a number of studies have demonstrated that this technique is advantageous to start performance due to the increase in horizontal take-off velocity. Consequently, swimmers are now utilising this technique during competition and this evolution in technique has highlighted the need to re-evaluate swimming start literature. The swimming start is typically broken into three phases; on-block, flight and underwater, with swimmers spending the longest amount of time in the underwater phase. The overall aim of this thesis was to investigate the main factors that affect the underwater phase of the swimming start. To achieve this, the thesis was broken into four sections; the first section characterised the elite swimming start using the kick-start technique and identified key parameters that affect overall start performance. The second section compared three underwater trajectories used by elite swimmers and found that the fastest trajectory is a trade-off between utilising a depth that would reduce resistance while not introducing excessive vertical translation. The third section investigated the relationship between drag, velocity and depth and how it affects the underwater phase. Using the findings from the first three sections theoretical recommendations were established for the ideal underwater trajectory that elite swimmers should adopt to reduce resistance and achieve better start performances. These recommendations were then implemented in the fourth section which aimed to determine if precise quantitative biomechanical feedback could be used to train swimmers to their ideal underwater trajectory. The outcomes of this research highlight the value of a multidisciplinary approach and provide recommendations which can be used practically by coaches and sport scientists in the future to effectively improve start performances.

**Student Declaration**

I, *Elaine Tor*, declare that the Doctor of Philosophy thesis titled "Factors affecting the underwater phase of the swimming start" is no more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

Signature: [redacted] Date: 3rd September 2015

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**List of Publications**

This thesis is supported by a number of peer-reviewed publications.

**Journal Publications**

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**Media Publications**

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**Tor, E.** (2014). Take your marks … the science behind the perfect swimming dive. Retrieved from: https://theconversation.com/take-your-marks-the-science-behind-the-perfect-swimming-dive-29392

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## Contents

**List of Figures**

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**List of Abbreviations**

| | |
|---|---|
| 3D | Three Dimensional |
| AIS | Australian Institute of Sport |
| A | Surface area |
| ATTRU | Aquatic Testing, Training and Research Unit |
| $C_D$ | Drag Coefficient |
| CI | Confidence Interval |
| cm | Centimetres |
| $F_D$ | Measured drag force |
| Fr | Froude Number |
| *g* | Gravity |
| GigE | Gigabit Ethernet |
| Hz | Hertz |
| ICC | Interclass Correlation |
| KP | Knowledge of performance |
| KR | Knowledge of results |
| *l* | Length |
| m | Metres |
| $m \cdot s^{-1}$ | Metres per second |
| mm | millimetres |
| N | Newtons |
| v | Velocity |
| W | Watts |
| ρ | Density |
| s | Seconds |

**Thesis Outline**

During the course of this thesis, seven manuscripts/full conference abstracts were prepared for publication in which the candidate is lead author. All publications included as a Chapter in this thesis closely relate to the subject matter and subsequently form a cohesive narrative. The publications and submitted manuscripts follow the style outlined by each journal or conference and consequently there are variations in formatting throughout each Chapter. These publications are initially brought together by a General Introduction (Chapter 1), which provides background information, highlights the research problem to be answered and outlines the overall aims of the studies. The Literature Review (Chapter 2) then contains an overview of swimming start biomechanics, drag research in swimming and the use of feedback as a learning tool.

To answer the research questions proposed, this thesis is then split into four sections. Section 1 (Chapters 3-5) focuses mainly on the swimming start, its importance and the characteristics of elite start performance, with a particular focus on the underwater phase. In addition, work was undertaken as part of this section to establish the reliability of the start analysis system used for testing. After the importance of the underwater phase was highlighted in Section 1 and the key parameters of the underwater phase identified, Section 2 (Chapters 6-7) explores three different underwater trajectories of the swimming start to determine which was the fastest and how individual preferences affected the results. Section 3 (Chapter 8) then investigates the relationship between drag, speed and depth in order to provide a theoretical basis for the findings in Section 2. Section 4 (Chapter 9) combines the findings of all previous sections and determines if biomechanical feedback can be used to train swimmers to their ideal underwater trajectory. The final Chapter of this thesis summarised the main findings and readdressed how each aim was resolved. Chapter 10 contains a general discussion that interprets the major findings; key research, practical applications and future directions. All of the citations and references from each chapter are also combined at the end of this thesis with specific Appendices to supplement the information presented.

# Chapter 1: General Introduction

## Chapter 1.0 General Introduction

The swimming dive start is a complex movement involving the reaction to a stimulus, the co-ordination of explosive movements of the arms, trunk and legs to propel the body forward with maximum velocity and the ability to maintain a streamlined position to minimise the loss of horizontal velocity in the water (Guimaraes & Hay, 1985). The international rules of swimming dictate that swimmers must resurface from the underwater phase before the 15 m mark following starts in all strokes, except for breaststroke (FINA, 2010). Total start time for elite swimmers is typically between six to eight seconds and is the time from the starting signal to when the centre of the swimmer's head reaches the 15 m mark (Cossor & Mason, 2001). The start phase can also be broken into three phases; on-block, flight and underwater (Cossor & Mason, 2001; Elipot, Hellard, Taïar et al., 2009; Hay, 1986; Thow, Naemi, & Sanders, 2012). The on-block phase is typically defined as the time between the starting signal and the time when the swimmer's feet leave the blocks. The flight phase begins when the feet leave the block and ends when the swimmer's head makes contact with the water. Finally, the underwater phase is defined as the interval between the head's contact with the water and the head re-surfacing.

Start times have been shown to be influential to overall performance during competition, contributing between 1-26% of total race time depending on the distance of the event (Lyttle & Benjanuvatra, 2005; Mason, Alcock, & Fowlie, 2007; Tor, Pease, Ball, & Hopkins, 2014). Race analysis at the 1998 World Swimming Championships in Perth showed high correlations between start time and overall performance, particularly in events 100 m or less (Mason, 1999). Further, correlational analysis of nine international competitions over a seven year period, Robertson et al. (2009) observed that fast starts were the most successful strategy in shorter events for improving performance. Additionally, Girold et al. (2001) found that for the women's 200 m freestyle the first 50 m of the race was the most important variable for medallists at the Sydney Olympics. Subsequently, any small improvements in time gained during the start phase of the race can be advantageous to many elite swimmers as it may result in significant improvements to overall competition performance (Breed & McElroy, 2000).

A number of start techniques have been examined in the literature due to different techniques being developed and changes in the start block itself. With the introduction of the Omega OSB11 starting blocks to international competition, many swimmers are now using a new kick-start technique during competition. The new start block consists of the main platform angled at 10°, an adjustable back plate, foot rest or kick plate angled at 30° to the main deck and can be moved to five locations at 35 mm intervals, starting at 350 mm from the front edge of the block. The performance differences between the 'kick-start' technique and earlier styles (such as the track start, grab start and swing start) mean that previous start literature may not be relevant to what swimmers are currently employing during competition. This thesis re-evaluated previous start literature and placed emphasis on the kick-start technique. Research concerning the on-block and flight phase of the kick-start has established that utilising the kick plate would allow swimmers to generate larger take-off horizontal velocities, which translate into faster start performances (Honda, Sinclair, Mason, & Pease, 2010). However, there is currently very little research focussing on the underwater phase of the kick-start. Hence, added attention was placed on the underwater phase of the swimming start in this thesis as it is the longest phase, has been identified as the most important part of the start and is when the swimmer is travelling at their fastest through the water. Further, this phase can make-up 95% of the variance in start time and has been identified as the most influential in determining efficient start performance (Guimaraes & Hay, 1985). As such, the main aim of this thesis was to investigate the factors that affect the underwater phase of the kick-start technique.

This thesis is broken into three sections; the first section of this thesis specifically focuses on characterising the kick-start technique and also identified which key parameters would affect start performance the most. Identification of these parameters using an elite sample would give coaches a means to formulate more specific training programs based on a scientific approach and provided the basis for the subsequent sections in this thesis. The second section explored three common underwater trajectories used by elite swimmers, which were determined during the first section of the thesis. While many of the main factors affecting the swimming start have already been explored, detailed analysis of the underwater trajectory used during the kick-start technique has not been completed using elite swimmers. A study on the influence of individual technique preference was also included in this section to justify the use of a comparative study design in applied elite swimming research.

The objective of the third section of this thesis was to investigate how drag affects the underwater phase. There are three types of drag acting on the swimmer; friction, form and wave drag. Frictional drag represents the drag produced as a result of friction between the water and the surface of the swimmer (Lyttle, Blanksby, Elliott, & Lloyd, 1998; Rushall, Holt, Sprigings, & Cappaert, 1994). Form drag occurs due to boundary layer separation around the swimmer, this separation in flow leads to the formation of large and small eddies which result in the creation of pressure difference between the leading and trailing edges of the body (Naemi, Easson, & Sanders, 2010; Rushall, Holt, Sprigings et al., 1994). Wave drag exists because as the swimmer travels through the water there is energy needed to generate waves at the surface of the water. Previous research has found that each type of drag would increase linearly, squared and to the power of six with velocity respectively. Thus, wave drag is the most deleterious type of drag and because of its difficulty to measure has not been widely investigated with human swimmers (Vennell, Pease, & Wilson, 2006).

The magnitude of wave drag is highly influenced by the speed and depth at which the swimmer is travelling (Rushall, Holt, Sprigings et al., 1994; Vennell, Pease, & Wilson, 2006). Wave drag is at its maximum just below the surface because as the swimmer travels closer to the surface the waves created on top of the water become larger. Therefore, reducing the amount of wave drag acting on the swimmer becomes important as the swimmer rises up to the surface during the underwater phase of the start to commence free swimming. This thesis determined how total drag and wave drag affect the swimmer with respect to speed and depth during the underwater phase. Using these advancements in drag research, coaches would be able to make recommendations to their swimmers about the depth that would reduce the influence of wave drag and total drag leading to improvements in start performance.

The final section of this thesis used findings from all of the previous sections to examine if augmented feedback coupled with a fading feedback schedule could be used to alter the technique of a complex skill such as the swimming start. Feedback is a broad term used to describe information about the performance of a skill which can be either intrinsic or extrinsic (Magill, 2007). Feedback from external sources is commonly termed augmented feedback and refers to information that individuals cannot detect for themselves. Delivering high quality and frequent augmented feedback has been shown as one method to reduce errors and increase the effectiveness of athletes' performance during skill acquisition. However, much of the present literature utilises simple single-jointed tasks that are not sport specific. Despite the known potential of biomechanical feedback to facilitating skill learning and performance, there has been surprisingly little research conducted on how best to utilise such information, particularly using complex multi-jointed skills (Abernethy, Masters, & Zachry, 2008). Thus, the approach established in this thesis can be used as a basis for feedback delivery that coaches can apply effectively in the daily training environment for skill improvement.

This thesis used a novel multi-disciplinary approach to research the elite swimming start, combining aspects of performance analysis, biomechanics and skill acquisition. The overall aim investigate the main factors that affect the underwater phase of the swimming start. The secondary objective of the thesis was to use biomechanical feedback to train swimmers to an individualised underwater trajectory based on the findings from previous studies within the thesis. The findings of this research would have practical implications that allow sport scientists to provide specific coaching cues concerning the key parameters for better start performances, which would ultimately lead to improved competition performance.

# Chapter 2: Literature Review

## Chapter 2.0 Literature Review

This thesis would bring together three different areas of scientific literature, including swimming start biomechanics, hydrodynamics and skill acquisition. There is currently very little research that combines these areas, particularly when applied to the swimming start.

### 2.1 The Grab-Start Technique

The grab start involves the swimmer grasping the front edge of the starting block with their hands either on the outside or the inside of their feet (Bowers & Cavanagh, 1975; Guimaraes & Hay, 1985; Jorgic, Puletic, Stankovic et al., 2010)(Figure 1). The grab start was originally thought to be the fastest start because the forces are travelling in the desirable horizontal direction from the beginning of the dive (Lyttle & Benjanuvatra, 2005). The grab start technique also places the swimmer's centre of gravity (CoG) further forward compared to other start techniques and because of the shorter distance to move, block time is significantly reduced (Bloom, Hosker, & Disch, 1978; Bowers & Cavanagh, 1975; Pearson, McElroy, Blitvich, Subic, & Blanksby, 1998). However, with the introduction of the Anti-Wave Olympic 2000 starting block for the Sydney Olympics, swimmers began to utilise the track start more commonly (Blanksby, Nicholson, & Elliott, 2002). In a study comparing grab start with the track start, Vilas-Boas, Cruz, Sousa et al. (2003) observed faster block time, higher impulse, greater flight distance and shorter glide time with the grab start over the track start.

**Figure 1 Grab-start technique**

## 2.2 The Track-Start Technique

The track start has many of the same principles as the grab start (Figure 2). The main difference between the grab and track start is the positioning of the feet on the blocks and this subsequently changes key variables that contribute to start time. The track-start has a wider base of support in the sagittal plane which allows the swimmer greater stability and a lower CoG resulting in greater horizontal impulse (Breed & McElroy, 2000). The change in foot and hand placement from the grab start to the track start also changes the take-off angle (increases) that in turn changes the angle swimmers enter the water (Pearson, McElroy, Blitvich et al., 1998). A change in take-off angle is also said to allow the swimmer to increase their potential flight distance, thereby potentially increasing their performance (Lyttle & Benjanuvatra, 2005).

**Figure 2 Track-start technique**

Many studies have aimed to compare different aspects of the grab start and track start techniques to determine which of the two is superior. However, differences in study designs have resulted in conflicting results within the literature. Toussaint, van Stralen, and Stevens (2002) and Issurin and Verbitsky (2002) claimed that the grab start is better than the track start, while Kirner et al. (1989) and Shin & Groppel (1984) claim no difference between the two. On the other hand, Juergens (1996) and Holthe and McLean (2001) found that the track start is better due a reduction in block time. Breed and McElroy (2000) compared the grab, swing and track start technique, using 23 female competitive athletes who did not specialise in swimming. The researchers' rationale behind the study was that having subjects who did not specialise in swimming would negate any bias a swimmer may have to their preferred starting technique. The subjects were taught the three techniques before being asked to perform two trials of each dive. They found that the swing start was the slowest for all subjects to 15 m. Furthermore, the take-off angle of the track start was significantly lower than the grab start and the track start had a significantly higher take-off velocity. Overall it was found that the greater contribution from the arms in the track starts and greater distance travelled through the air resulted in the best starting technique. Further to this Welcher, Hinrichs, and George (2009) investigated the differences between front and rear weighted track and grab starts. Twenty female collegiate swimmers were tested and it was found that a rear-weighted start had a longer block time, greater velocity at take- off and shorter 5 m split time over a front weight weighted start. In particular, the rear-weighted track start was shown to be the fastest start type to 5 m as it is assumed that greater horizontal impulse can be generated. This study only examined time to 5 m and did not take into account the underwater phase, hence this thesis would examine 5m, 7.5 m, 10 m and 15 m split times to provide a more comprehensive analysis of start performance.

Investigating specific parameters of the grab, swing and track starts, Jorgic et al. (2010) used flight time, block time, start time, 5 m, 7.5 m, 10 m and 15 m split times, reaction time, angle of take-off, angle of entry, take-off velocity and centre of mass velocity to investigate the difference between grab and track starts. Six competitive swimmers with at least six years of experience were used in this study. The subjects were taught the three techniques before being asked to perform two trials of each dive. Results showed that the grab start had a, non-significant ($p < 0.05$), 0.23 m longer flight length. The only significantly different technical parameter was angle of take-off, which was larger for the grab start. They also found that the swing start was the slowest for all subjects. Furthermore, the track start had a significantly higher take-off velocity. Consequently, a number of studies have found that the track start was superior when compared to the grab and swing starts.

As previously mentioned, there have been multiple studies that have characterised and compared the grab and track start techniques. An important aspect when examining those previous studies is the frequent lack of consideration of the swimmer's preferred technique by the authors. Vilas-Boas et al. (2003) and Vantorre, Seifert, Fernandes, Vilas-Boas, and Chollet (2010) were the only two studies to take this into account. Given this, the findings from previous studies may not be conclusive, highlighting the need for further research based on the current techniques used by elite swimmers. A study has been included in this thesis that accounts for the swimmers' personal preference.

## 2.3 The Kick-Start Technique

After the 2008 Beijing Olympics a new start block was introduced to all international competition (Honda et al., 2010). This new start block was first used in international competition at the 2010 Commonwealth Games in Delhi (Slawson, Conway, Cosser, Chakravorti, & West, 2013). The new start block is called the Omega OSB11 and consists of the main platform angled at 10°, an adjustable back plate, foot rest or kick plate angled at 30° to the main deck and can be moved to five locations at 35 mm intervals, starting at 350 mm from the front edge of the block. The additional kick plate has allowed for the development of a new start technique called the kick-start.


**Figure 3 Omega OSB11 Starting Block**

Despite, research on the new start technique being scarce, studies that have compared start styles to the kick-start have suggested using the new technique is advantageous (Barlow, Halaki, Stuelcken, Greene, & Sinclair, 2014; Biel, Fischer, & Kibele, 2010; Honda, Sinclair, Mason et al., 2010; Nomura, Takeda, & Takagi, 2010; Takeda, Takagi, & Tsubakimoto, 2013) This is due to Omega's claiming that the kick plate enables the swimmer to push-off with a rear knee angle of 90°, which allows for optimal force production. Due to the perceived benefits this start is now utilised by most swimmers during competition.

The start position configuration of the kick-start has also been studied. Honda et al.(2012) investigated block position by testing kick plate position and changing the position of the swimmers' weight prior to leaving the block. Through the use of elite swimmers it was found that a neutral-weighted to slightly rear-weighted kick start on the swimmers' preferred kick plate setting was the best combination to produce the best dive performance (Honda et al., 2012). However swimmers' were asked to perform an un-preferred technique, results may have been skewed in favour of the swimmers' preferred technique. Consequently, future start studies should take into account the swimmers preferred technique.

Comparisons between kick-start and track-start performance has also been previously examined. Murrell and Dragunas (2013) compared the kick-start technique to the grab start and found that the newer start was faster to 2 m on all occasions. This study contained low subject (n=4) numbers, did not allow swimmers to place the kick plate at their desired position and only used time to 2 m not time to 15 m (the normal criterion measure for start performance). Similarly, Honda et al. (2010) found that the kick-start was faster than the track-start to 5 and 7.5 m. This was due to a faster block time and greater horizontal impulse. However, this study assessed dive performance using a "dive and glide" technique to eliminate the influence of other underwater variables; potentially changing the results when full dive performance to 15 m was assessed. All studies in this thesis were able to expand on these findings by examining full start performances.

## 2.4 The Sub-Phases of a Swimming Start

Each swimmer may have a unique start technique but a set distance is used to define all start performances. Total start time is calculated as the time from the starting signal to when the centre of the swimmer's head reaches the 15 m mark (Cossor & Mason, 2001). The international rules of swimming dictate that swimmers must resurface from the underwater phase at the 15 m mark following starts in all strokes, except for breaststroke (FINA, 2010). During analysis the start is typically broken into three phases, regardless of the type of start used, the sub-phases remain the same; each contributing to overall start performance (Bloom, Hosker, & Disch, 1978; Cossor & Mason, 2001; Seifert, Vantorre, & Chollet, 2007). These phases are referred to as; on-block, flight and underwater (Cossor & Mason, 2001; Elipot et al., 2009; Hay, 1986; Thow et al., 2012). The sub-phases are described in detail below.

*On-Block Phase*

The on-block phase is the time from the starting signal to when the swimmer's toe leaves the block (Guimaraes & Hay, 1985; Issurin & Verbitsky, 2002; Ruschel, Araujo, Pereira, & Roesler, 2007).Total on-block time is a combination of reaction time (the interval between the starting signal and the first movement on the block) and movement time (Garcia-Hermoso et al., 2013). However, there has been some evidence that this phase changes depending on the swimmer's speciality event.

Regardless of event, a faster block time has been shown to directly relate to improvements in overall start performance (Garcia-Hermoso, Escalante, Arellano et al., 2013; Vantorre, Seifert, Fernandes, Vilas-Boas, & Chollet, 2010). However a reduction in block time may be linked to lower impulse and thus lower resultant peak forces. A reduction in impulse would also result in a lower take-off horizontal velocity and would significantly affect subsequent phases of the start (Lyttle & Benjanuvatra, 2005). Slawson et al. (2013) also stated that a shorter block-time, higher take-off velocity and greater distance of entry does not equate to better start performanes on all occasions. For example, a greater take-off horiztonal velocity may lead to a larger entry hole, resulting in increased drag. This suggests that during the on-block phase there is a trade-off between time on block and force produced (Breed & Young, 2003). By utilising the kick-start technique, research has shown that swimmers are able to generate slightly shorter block times without sacrificing take-off horizontal velocity (Honda et al., 2010; Slawson et al., 2013). Honda et al. (2010) suggest this is because the additional kick plate allows the back leg to be in a more advantageous position for force production. Furthermore, similar to Honda et al. (2010), Garcia-Hermoso et al. (2013) utilised a large amount of elite competitive data to compare on-block times between the track and kick – starts. They found that there were shorter on-block times when using the kick-start and this was a determining factor, particularly in the women's 50 m events. As such, using the kick-start technique would generally allow swimmers to gain an added advantage for better start performances over other start techniques.

*Flight Phase*

The flight phase is typically defined as the time from when the swimmer's toe leaves the block to when the swimmers' head enters the water. In theory, swimmers would be able to travel faster through the air than through water due to less resistance. However, flight duration is not usually correlated with start time; it is flight distance that is a determining variable of performance (Ruschel et al., 2007). Hence, to improve start performance, swimmers should theoretically maximise the flight phase by increasing entry distance. However research has shown leaving the block with higher horizontal velocity results in an increased entry distance, at the cost of a larger entry hole size and flatter trajectory (Costill, Maglishco, & Richardson, 1992; Kirner et al., 1989). A flatter trajectory would also result in a shallower underwater trajectory, leading to more drag acting to slow the swimmer down. Similar to the on-block phase there is a trade-off, such that the length of the flight phase is a compromise between take-off horizontal velocity, take-off angle and entry distance (Miller, Hay, & Wilson, 1984).

*Underwater Phase*

The underwater phase is typically defined as the time from when the swimmers' head enters the water to when the swimmer resurfaces again to commence free swimming. The underwater phase can be further subdivided into the glide phase and the underwater kicking phase. During the glide phase the swimmer is travelling at their fastest through the water and typically adopts a streamlined position with their arms outstretched. The underwater phases are crucial to overall race performance because, after the dive itself, this is the next fastest section of the race

(Connaboy, Coleman, Moir, & Sanders, 2010). This phase has also been identified as the most decisive in order to achieve faster overall start performances (Cossor & Mason, 2001; Elipot et al., 2009; Thow et al., 2012). The average speed during this phase is highly dependent on horizontal velocity at penetration into the water and drag forces acting on the swimmer during the glide phase (Lyttle & Benjanuvatra, 2005).

Correlation analysis of start performances at the Sydney 2000 Olympics by Cosser and Mason (2001) found that underwater distance during the start was negatively correlated to overall start performance for the men's 200 m butterfly, 100 m backstroke and 100 m freestyle races. This would suggest that as the swimmers swam longer underwater start time to 15 m improved due to a greater underwater velocity being maintained by these swimmers. Similar to the men's events the analysis of the women's events showed that those swimmers who travelled further underwater were able to achieve faster overall start times. However, Cosser and Mason (2001) did not examine any extra factors such as maximum depth or timing of first kick in their study. Therefore, a more detailed analysis of the underwater phase would be able to identify the sub phases and specific elements within the underwater phase that influence overall start time the most.

Another study by Elipot et al. (2009) aimed to determine the swimmers' loss of speed during the underwater phase of the start. The rationale for this was to estimate the distance between the swimmer and the start wall when the swimmer's velocity decreases and to identify the factors influencing this loss of speed. Eight swimmers performed three grab starts to the best of their ability. Nine anatomical landmarks were then identified to allow the calculation of velocity curves. A principal components analysis was used to determine the factors which influenced glide performance the most. Results showed that following a start entry, swimmers should hold their streamlined position until the centre of mass reaches a mean distance of about 5.63 and 6.01 m (Elipot et al., 2009). If a swimmer waited too long to start leg movements they would lose approximately 0.4 $m \cdot s^{-1}$ and if a swimmer were to commence their leg movements prematurely they would cause higher hydrodynamic resistance and lose speed. However, with the introduction of the new starting blocks the grab start (which was used by Elipot et al. (2009)) has been phased out in favour of a kick start (Jorgic et al., 2010). Given this, not all of these previous results would be applicable to current elite swimmers. As such, the studies in this thesis would utilise the kick-start technique which would be able to expand on the previous findings and lead to improvements in start performance.

Similarly, Houel, Elipot, Andre, and Hellard (2012) conducted a detailed three dimensional (3D) analysis of the underwater phase. Focusing on at the glide, this was the first study to provide such detailed recommendations on strategies to improve the underwater phase of the swimming start. The authors suggested that swimmers should apply three principles to improving the glide phase of the swimming start; to remain as streamlined as possible, to start underwater undulatory kick after 6 m using only the feet and legs and to improve the kick frequency of underwater undulatory swimming. Nevertheless this study utilised the grab start and it was unclear in the methodology how many trials were conducted. Thus, these findings may not apply to the kick-start technique given the differences in take-off horizontal velocity and entry.

**2.5 The Basics of Hydrodynamics**

Since water is an incompressible fluid, any movement executed by an aquatic animal or swimmer would set the surrounding water in motion and vice versa (Sfakiotakis, Lane, & Davies, 1999). Fluid resistance of the swimmer depends primarily on the boundary layer between the body surface and the free flow around the body (Hertel, 1969)(Figure 4). The boundary layer theory states that there are two layers of flow around the body. These two regions are divided into one layer that is close to the body and the other being the volume beyond the region close to the body's surface. One layer is laminar flow, which is characterised by smooth motion of fluid in layers while the other is turbulent flow, which refers to the flow that moves in all directions slightly as it moves forward (Hertel, 1969; Naemi et al., 2010). When the flow regiment is laminar, separation at the body surface starts almost as soon as the pressure gradient becomes adverse and a larger wake forms. On the other hand when the flow is turbulent flow separation is delayed and the corresponding wake is smaller and therefore there is a decrease is pressure drag (Marinho, Reis, Alves et al., 2009). Under equal conditions the laminar resistance is substantially lower than the turbulent resistance.

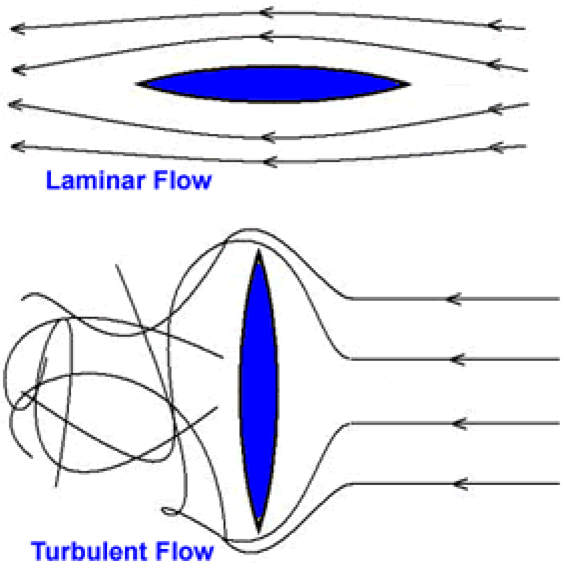



**Figure 4 Visual representation of laminar and turbulent flow (Bixler 2005)**

The water flow characteristics are typically hard to measure directly and therefore the estimation of laminar and turbulent flow is estimated using the Reynolds Number ($R_e$) (Hertel, 1969). The non-dimensional parameter $R_e$ is represented by:

$$R_e = vl/ \nu$$

Where v = swimming velocity, l = length of the body and $\nu$ = kinematic viscosity of the water. Studies show that as human swimmers move through the water the majority of flow around the body would be turbulent, resulting in greater total drag (Clarys, 1979). This highlights the importance of developing strategies to reduce drag, particularly during the underwater phase of the swimming start where preventing deceleration from excessive resistance is paramount.

## 2.6 Drag Coefficient

The resistance experienced as a swimmer travels though water is known as hydrodynamic drag. The main method of categorising drag is based on the actions of the swimmer and how the drag is created. Consequently, there are two types of drag; passive drag, which is when the swimmer is in a fixed position (streamlining following a start) and active drag, which refers to drag while the swimmer is actively kicking or stroking (Bixler, 2005).

Drag coefficient ($C_D$) is a number used to estimate the amount of drag acting on the vessel or swimmer. Drag coefficient is a function of the water flow characteristics determined by the swimmer's shape and size (Cappaert, Kolmogorov, Walker et al., 1996; Havriluk, 2005) It is also an indication of the amount of drag acting on the swimmer. The equation for $C_D$ is:

$$C_D = 2F_D/\rho V^2 A$$

Where $F_D$ is the total drag force, ρ is the density of the water, ν is the velocity that the swimmer is travelling at and $A$ is the cross-sectional area of the swimmer relative to the direction of travel (Bixler, 2005; Havriluk, 2005).

Drag coefficient also varies with speed, with Alley (1952) reporting that $C_D$ decreases for velocities between 0.6 $m \cdot s^{-1}$ and 1.52 $m \cdot s^{-1}$ due to a decrease in frontal area when being towed at the surface. However, for velocities above 1.52 $m \cdot s^{-1}$ there were increases in $C_D$, while the authors did not specifically measure wave drag they reported a noticeable bow wave that increased in size as velocity increased. More recently Vennell et al. (2006) reported increases in $C_D$ with velocity at the surface, although, this was not the same for swimming at all depths as the magnitude of each drag component also changes with depth.

**2.7 Resistance in Swimming**

The resistive or drag forces during swimming act opposite to the direction of the motion. These forces are related to the water flow around the body and how the body interacts with that flow. There are three main forms of drag; form, friction (or skin), and wave (Bixler, 2005; Lyttle et al., 1998; Naemi et al., 2010; Naemi & Sanders, 2008; Sheehan & Laughrin, 1992; Vennell et al., 2006). Frictional drag represents the drag produced as a result of friction between the water and the surface of the swimmer when water passes over the body surface, and is reported to increase linearly with an increase in swimming velocity (Lyttle et al., 1998; Rushall, Holt, et al., 1994; Sheehan & Laughrin, 1992). The main two factors that affect frictional drag are body surface area and type of surface. These two factors would change the flow of the boundary layer around the swimmer. Any irregularities in the surface would result in more turbulent flow where small eddies are formed next to the surface and absorb energy resulting in more frictional resistance (Rushall, Holt, Sprigings et al., 1994). While on the other hand, having a completely smooth or oiled surface may not necessarily be advantageous to performance, as the resistance of oiled skin repelling the water is greater that the friction of water on skin (Bixler, 2005). The ideal situation for reducing friction drag is a smooth granulated surface such as shaved skin that creates a thin layer of water that adheres to the skin, essentially resulting in friction between water and water which is much less than water and skin. Larsen, Yancher, and Baer (1981) estimated the frictional drag component to comprise 18 to 20% of total drag in boats. However, the relative contribution of friction drag to total drag in humans is much harder to determine due to the non-streamlined nature of the human body (Gadd, 1963).

Form drag is the result of the differences between pressure at the leading and trailing edges of the body (Naemi et al., 2010). Form drag is named so because the shape and form of an object or swimmer can play a major role in determining when the boundary layer separates and the severity of what the form drag would be (Bixler, 2005). Specifically, form drag is related to the cross sectional body surface area of the swimmer causing boundary layer separation. Boundary layer separation behind the swimmer is a main cause of the differences in pressure (Bixler, 2005). This separation in flow leads to the formation of large and small eddies which result in the creation of form drag because the eddies exert less pressure on the body than the water in the upstream section that have not yet separated from the body (Naemi et al., 2010; Rushall, Holt, et al., 1994). Certain technique changes such as lifting the head to breathe, dropping the legs and the angle of attack would affect the amount of drag due to an increase in projected area exposed to the water (Naemi et al., 2010). Angle of attack is the angle between the reference line on a body and the vector representing the relative motion between the body and the fluid it is moving through. Hence, the greater deviation from the streamlined position while travelling though the water would result in earlier boundary later separation and greater form drag acting on the swimmer (Rushall, Holt, et al., 1994). Form drag is reported to increase by the square of velocity and becomes increasingly more important the faster the swimmer travels (Bixler, 2005; Rushall, Holt, et al., 1994).

Wave drag occurs when swimming at or near the surface of the water when the swimmer and the movement of body segments create waves. Wave drag is said to be the most deleterious of all the types of drag because it increases to the sixth power of the swimmer's velocity (Lyttle et al., 1998; Vennell et al., 2006) and is mainly due to energy lost in creating wave systems around the vessel or swimmer (Vennell et al., 2006). If a body is swimming below the surface deep enough and at a sufficient enough distance from the bottom the flow of water around the body is the same as if the body were flying in free air space (Hertel, 1969). When the swimming body moves closer to the surface the resistance increases and waves are generated on the surface of the water. Early towing research found that the minimum resistance was achieved when the body was submerged at a depth equal to approximately three times the diameter of the body of revolution (Hertel, 1969). The maximum resistance occurred when the body was lying directly under the undisturbed water level. The amount of resistance measured here was about five times the minimum resistance (Hertel, 1969). With this in mind it is necessary to determine how the influence of wave drag changes and affects the swimmer as they rise to the surface following a dive start.

Towing swimmers through the water at various speeds in a streamlined position is a common way to measure passive drag and conduct detailed analysis on the relationship between drag and speed (Clarys, 1979; Lyttle & Blanksby, 2000; Lyttle, Blanksby, Elliott et al., 1998)There are currently conflicting results between the few studies which have investigated drag forces underwater. Clarys (1979) reported 20% higher drag values when being towed underwater compared to the surface whereas Maiello et al. (1998) found higher drag force at the water surface. A limitation of these two studies was towing speed not being fast enough to translate into the speeds which swimmers would be travelling at during the start and turn phase of a swimming race. In another study using higher velocities, Lyttle et al. (1998) sought to establish the optimal gliding depth and velocity using faster velocities which mimicked the speeds travelled by elite and club swimmers during the turn phase. The results from this study found that at velocities higher than 1.9 $m \cdot s^{-1}$ swimmers should aim to perform their glides approximately 0.4 m underwater to gain maximum drag reduction methods. A 15-18% decrease in drag was found at this depth when compared to gliding at the surface (Lyttle et al., 1998). In the same study by Lyttle et al. (1998), total body drag force reduced at the velocities of 1.6 $m \cdot s^{-1}$ and 1.9 $m \cdot s^{-1}$ when swimmers were kicking while being towed.

Additionally, there is one study that disagrees with other similar passive drag studies. Jiskoot and Clarys (1975) reported that swimmers experienced 20% higher drag 0.6 m below the surface compared to swimming at the surface. Jiskoot and Clarys (1975) used velocities that were slower than speeds produced by swimmers in competition (1.5-1.9 $m \cdot s^{-1}$), particularly during the start phase and did not describe how depth was controlled. The results from Lyttle et al. (1998) differ from Clarys (1979) because wave drag is expected to contribute more to total resistance as velocities increase. Hence, at the low velocities of 1.5 – 1.9 $m \cdot s^{-1}$ used by Clarys (1979) and Jiskoot and Clarys (1975) would not have been high enough to produce a substantial amount of wave drag. More research which isolates the contribution of wave drag on human swimmers would be beneficial in determining the optimal depth swimmers should travel at, particularly during the underwater phase of a swimming start.

Even though towing is a common method to estimate drag, there are limitations associated with previous towing systems. These include the inability to sufficiently control towing velocity and depth, unnatural streamline towing positions and the use of towing at speeds which are less than that used during starts and turns. To overcome this problem Vennell et al. (2006) used mannequins and a flume to conduct their drag research and Bixler et al. (2007) used a CFD model. However, a disadvantage of these methods is that they do not take into account positional changes that naturally occur during swimming. Further, these methods can be time consuming and as a measurement of drag CFD, has an ability to model the complete surface of the body using software designed to model flow over solid bodies (Naemi et al., 2010).

### 2.8 Wave Drag and Depth

Depth of travel has previously been identified as a major factor in the amount of wave drag acting on the swimmer (Rushall, Holt, et al., 1994). Hertel (1969) found that the maximum drag coefficient was found when a spindle-shaped object was directly below the surface. In this case the drag coefficient was five times the minimum drag measured on the deeply submerged object. However, the coefficient decreased significantly when the body was brought up and broke the surface to become zero when the spindle was completely out of the water. Therefore, for both aquatic animals and humans swimming just beneath the water surface is the worst possible position (Videler & Nolet, 1990).

Wave drag becomes more important when speed increases. Research has found that wave drag contributes anywhere between 5%-45% at speeds of 2 $m \cdot s^{-1}$ when swimming at the surface, although, this number is significantly lower when swimming at a depth of 0.6 m, as there are less wave drag  as the swimmer travels deeper below the surface (Vennell et al., 2006). There is a reduction in wave drag at increasing depths below the surface; research by Larsen et al. (1981) suggests that a swimmer should glide at a depth of approximately 0.2 times the swimmer's length. This equates to a swimmer with a reach height of 2.5 m travelling at a depth of 0.5 m below the surface. Previous research on humans has also shown that swimmers must be deeper than 1.8 chest depths and 2.8 chest depths below the surface for velocities of 0.9 $m \cdot s^{-1}$ and 2.0 $m \cdot s^{-1}$ respectively to avoid wave drag (Vennell et al., 2006). This is equivalent to water depths of 0.45 m and 0.70 m respectively for a swimmer with 0.25 m of chest depth. As the body moves close enough to the surface of the water for the distorted flow to impinge on the surface there are pressure changes due to the Bernoulli Effect. These pressure changes cause depressions and elevations in the water's surface around the body which then create a wave wake. It is at this point when the body begins to experience wave drag. The closer the body is to the surface of the water the larger the disruption to the flow at the surface and therefore greater wave drag (Vennell et al., 2006; Videler, 1993). Consequently, wave drag would be heavily affected by both speed and depth and this relationship was investigated in more detail within this thesis.

In a novel study which separated the value of wave drag, Vennell et al. (2006) towed mannequins through a flume at different speeds and depths. At shallower depths and higher speeds the Fr > 0.45 (> $2.2 m \cdot s^{-1}$) there is a more gradual increase in drag as the mannequin may be generating some dynamic lift as it moves towards planning at the surface. Furthermore, at lower speeds where Fr < 0.15 it was found that drag coefficient estimates were not reliable as they result from the ratio of small numbers where velocities were under $0.6 m \cdot s^{-1}$ and drag values were under 8 N. At Depths of 1.0 m and 0.8 m there was no distorted flow around the mannequin and the water's surface. The drag curves and contour plot showed an increase in drag as the mannequin approached the surface (Vennell et al., 2006). When the mannequin was towed at lower speeds and shallow depths some of the mannequin was out of the water which would mean that both skin and form drag may affect the total drag measurement. Hence, new measurement techniques need to be developed which isolate just the wave component of drag (Vennell et al., 2006). This study was only limited to passive drag and did not investigate the swimmers glide at the surface or influences of wave drag.

In a similar study using mannequins, Pease (2010) investigated the effect of angle of attack and depth on passive drag, with a specific focus on wave drag. This is important, particularly when using towing methods to assess drag with human swimmers. Pease (2010) mounted a mannequin in a flume at angles of attack of -4, -2, 0, +2 and +4$^{o}$ respectively. At each of these angles of attack, depths of 0.2 – 0.8 m (0.1 m increments) and 13 velocities from 0-2.55 $m \cdot s^{-1}$ were used to obtain drag-velocity curves. The results showed that a slight negative angle of attack at the free water surface would provide a reduction in the contribution of wave drag and therefore, total drag acting on the swimmer. Only small effects were found which suggests that the effects of depth would still outweigh changes in the angle of attack. However, as this study used mannequins instead of humans, caution should be used when generalising the findings.

## 2.9 Wave Drag and Speed

Another major determinant of wave drag is the speed the swimmer is moving through the water. Swimmers and vessels moving at any speed on the surface of the water would create waves which would form a wake behind them (Vennell et al., 2006; Videler, 1993). When travelling at high speeds the Froude number (Fr) is used to measure the drag on the surface of the water which is created by the energy needed to make the waves (Vennell et al., 2006). The Froude Number is used because the main forces needed to generate waves are inertia and gravity forces (Bixler, 2005). Froude number is a common ratio of inertial and gravitational forces and is used to empirically characterise the propensity of an object to generate waves (Larsen et al., 1981). The equation for Froude number is:

$$Fr = \frac{v}{\sqrt{gl}}$$

where V = vessel speed, g = 9.81 , L = length of the vessel. This number is important when describing wave drag, when Fr = about 0.25 the drag increases rapidly due to the increasing importance of wave drag (Vennell et al., 2006).

Froude number can also be used to determine the swimmer's limiting velocity for gliding at the surface (Naemi et al., 2010; Vennell et al., 2006). A taller swimmer would have smaller Fr number than a shorter swimmer when tested at the same speed and therefore experience less wave drag acting on them. Larsen et al. (1981) has reported the maximum Fr a swimmer can achieve approximately 0.42 or 0.45 (Videler, 1993). This has practical significance to swimming because once Fr number reaches this range propulsion from stroking would have little effect on increasing swimming velocity due to large increases in wave making. This is typically referred to as hull speed and is when the vessel's speed matches that of a wave which has a wavelength equal to the length of the vessel, one way to overcome this to hydroplane above the surface of the water (Vennell et al., 2006; Videler, 1993). Hence, once the Fr of an object is known the steady-state wave drag may be determined using the equation and hull speed can be calculated.

With very little research isolating the measurement of wave drag on human swimmers, there is a need to formulate research in this area in order to apply these findings practically to swimming. This is particularly needed during the underwater phase of the swimming start, as wave drag is one of the major factors that would affect the speed achieved by the swimmer as they rise to the surface to commence free swimming.

**2.10 Measurement of wave drag**

Knowledge of the magnitude of the hydrodynamic drag forces at various depths and velocities could enable technique changes that reduce deleterious drag (Rushall, Sprigings, Holt, & Cappaert, 1994). Very few studies have analysed underwater drag using human swimmers. The need to investigate the influences of drag underwater arises from the swimmers remaining underwater for part of all four competitive strokes, therefore instrumentation which quantifies passive and active drag during these phases is able to determine techniques to reduce drag (Lyttle, Elliot, Blanksby, & Lloyd, 1999). Total drag can either be measured directly based on calculations on the kinematics of a gliding body or using a method such as towing. When measuring drag through a towing device, the total drag force is equal to the towing or holding force.

Since wave drag is a large proportion of total drag a direct estimation of wave drag using wave patterns is advantageous (Eggers, Sharma, & Ward, 1967). Through numerous research studies it has been found that wave analysis can be simplified by the introduction of suitable non-dimensional variables (Eggers et al., 1967). One limitation during wave pattern analysis is that the analysis should be treated as a steady-state problem so that all transient effects and time dependencies can be neglected in a coordinate system moving with the ship (Eggers et al., 1967). There are also two very important assumptions, the first is that the ship or swimmer are moving either on the horizontally unbounded deep water or in a tank of such large dimensions that they can practically be considered as infinite. The second is that water is an incompressible ideal fluid so that ships or swimmers movement through fluid can be described as a mathematical function. There are a number of mathematical methods for calculating wave drag which includes the transverse cut, longitudinal wave cut and X,Y methods. This thesis will utilise the longitudinal cut method (LWC) to estimate wave drag with the use of acoustic sensors. The LWC method involves the measurement of one or more wave profiles along a straight track parallel to the direction of motion (Eggers et al., 1967). This is generally achieved in experiments by locating a stationary wave probe and taking a time dependent record of wave height as the ship or swimmer passes by. One longitudinal cut is taken on either side of the ship or swimmer before a series of mathematical formulas are used to determine wave patterns. These equations are reports in Eggers et al. (1967). The main limitation of the LWC method of wave drag measurement is that it does not take into account the wave reflection from the tank walls (Eggers et al., 1967). LWC can only be applied where the wave data used for analysis is taken in a region where the wave patterns are unaffected by reflection. This limitation was accounted for in this thesis by towing subjects in a large competition sized swimming pool without lane ropes to decrease any change of wave reflection. This thesis will be one of the first to utilise the LWC method on human swimmers to isolate the measurement of wave drag.

## 2.11 Definitions of Feedback

The next sections of this literature review would explore the link between augmented feedback and motor skill learning, particularly focussing on multiple-joint skills that are sport specific. Learning a new skill in sport requires the coordination and control of limb and body movements (Baudry, Leroy, Thouvarecq, & Choller, 2006). Most behavioural researchers define learning as the relatively permanent change in the underlying capability for responding (Salmoni, Schmidt, & Walter, 1984; Winstein & Schmidt, 1990). When delivering biomechanical feedback it is important to consider the fundamental differences in the manner in which learning can occur. Learning is not directly observable or quantifiable which is why learning is measured indirectly though performance changes. Performance refers to an observable execution of a motor skill and can be quantified in terms of outcome and form (Abernethy et al., 2008).

The aim of motor learning is to integrate motor control processes through repeated practice to identify and permanently adopt a more optimal movement technique (Moran, Murphy, & Marshall, 2012). Feedback provides information about these motor control processes and movement. Feedback is any performance related information that can tell the performer something about the outcome or process that caused the outcome of a particular motor skill (Abernethy et al., 2008; Magill, 2007). Feedback is essential for the process of learning and fundamental to learning a new task or refining an already learned skill. There are two main types of feedback (Figure 5); task-intrinsic feedback, which is the sensory-perceptual information that is a natural part of performing a skill, and augmented feedback that refers to any information provided external to the person performing the skill (Magill, 2007).

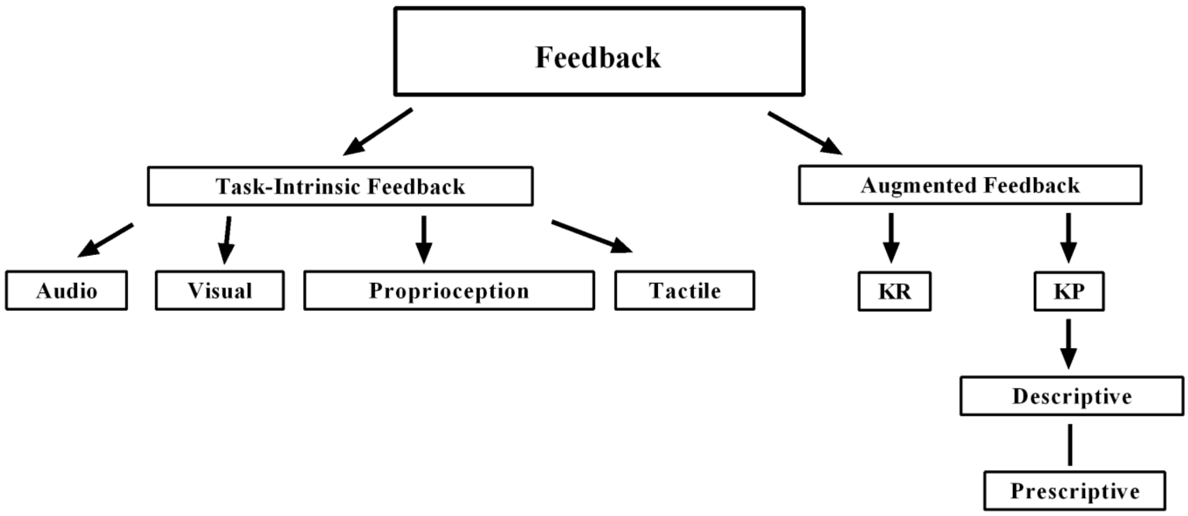



**Figure 5 Schematic diagram of feedback types (adapted from (Magill, 2007))**

Augmented feedback can be in the form of, knowledge of results (KR) or knowledge of performance (KP). KR refers to feedback about the outcome of the skill or about achieving the goal of the performance. KP refers to feedback about the movement that led to the performance outcome. Within KP there are two further types of feedback, these are; descriptive KP which is a statement only that describes the error a person has made during the performance of a skill and prescriptive KP which describes the errors made during the performance and then states what needs to be done to correct them (Magill, 2007).

There are a number of ways augmented feedback can enhance motor skill learning (Phillips, Farrow, Ball, & Helmer, 2013). The first is that augmented feedback provides outcome-based information that allows the athlete to determine what they must do to achieve efficient movement patterns (Magill, 2007). The second is that augmented feedback can be used to improve performance by providing information about specific contexts and situations. The final function of augmented feedback is it can promote motivation to continue to practice a skill or to continue to participate. Augmented feedback also provides added information about a skill that the performer cannot detect with his/her sensory system (Phillips et al., 2013).

The major issue when assessing various feedback techniques in sport is that there are many sources of information provided to the learner that can have confounding effects on performance (Salmoni et al., 1984). The distinction between learning and performance is often difficult which is why researchers would also typically use a transfer design with a retention test to assess learning (Magill & Anderson, 2012). If sufficient time is provided between the post-test and the retention test, it can be argued that the temporary effects of the feedback manipulation have dissipated and consequently the remaining effects are relatively permanent (Salmoni et al., 1984). No-feedback practice during a transfer design also tends to stabilise performance. Therefore, a transfer design with a no-feedback retention test is essential for unravelling the temporary effects of feedback manipulations from their relatively permanent learning effects. This thesis utilised a no-feedback retention study design to appropriately assess the effects of learning.

### 2.12 Frequency and Scheduling of Feedback

The scheduling of augmented feedback is very important (Anderson, Magill, & Sekiya, 2001). If feedback is scheduled incorrectly it can prevent the learner from processing important sources of task-intrinsic feedback or engaging in important aspects of action planning that are essential to movement task success (Magill & Anderson, 2012). Feedback is usually provided for a number of reasons; to the performer either prior to the task to shape the performer's practise attempt, about a particular aspect of their movement or after the task has been executed. Feedback schedules that accelerate the rate of performance improvement early in the acquisition phase (typically when feedback is presented immediately after each trial) tend to promote dependence. While schedules which slow the rate of performance improvement in acquisition tend to discourage dependence and as a result allow for more effective learning (Anderson, Magill, & Sekiya, 2001). Throughout the literature there has been some uncertainty as to the optimal amount of feedback to facilitate skill learning. When evaluating learning using a transfer test design researchers have found that increased feedback frequency can in fact degrade learning rather than facilitate it (Wulf & Schmidt, 1994). The feedback schedules that have been shown to be the most effective are those which manipulate relative feedback frequency, hence the percentage of trials that receive feedback is reduced. However, more research is needed, particularly using more complex tasks to determine the optimal feedback schedule to facilitate learning. Indeed, many factors need to be considered such as skill level of the performer, complexity of the movement, mode of feedback and length of intervention before prescribing an appropriate feedback schedule. The current body of research is scarce when relating feedback schedules to complex sport specific movements.

The frequency of feedback can be measured in two ways; absolute (the total number of trials that receive feedback) and relative (the proportion of the total trials having feedback provided). Augmented feedback is most effective when it facilitates the learners' information processing of critical sources of task-intrinsic feedback that is essential for controlling performance in the absence of augmented feedback (Magill & Anderson, 2012). Frequent feedback produces quite varied movements, which can prevent the learner from developing a stable movement representation (Wulf, Shea, & Matschiner, 1998). However, this generalisation does not necessarily apply to the learning of more complex motor skills. Guadagnoli, Dorneir and Tandy (1996) examined task-complexity and the amount of feedback given. They found that relatively high frequency feedback was more beneficial for the learning of complex tasks. Guadagnoli et al. (1996) suggested that to optimise the learning of complex tasks or when the performer has little task experience shorter feedback frequencies should be employed. While, Wulf et al. (1998) used a complex ski simulator task and found that subjects provided 100% feedback developed an error-detection and correction mechanism that enabled them to demonstrate further performance improvements even in the absence of feedback. The 50% group did not perform as well in a retention test as the 100% feedback group but they still performed better than a no feedback group. Consequently, the optimal feedback frequency would depend on the relative difficulty of the task and the task experience of the performer. These findings support a number of previous studies which suggest that providing learners with lower relative feedback frequency would result in more efficient learning (Gaudagnoli et al., 1996).

Another consideration for feedback scheduling is whether to provide the information concurrently (while the skill is being performed) or delayed (after the skill has been performed). Delaying augmented feedback has shown to be better for learning than giving feedback immediately after or concurrently with the movement (Magill & Anderson, 2012). While, concurrent feedback is proposed to be more detrimental than post response feedback because it produces a greater dependency on the feedback. Swinnen, Schmidt, Nicholson, and Shapiro (1990) asked subjects to perform a simple motor task and were either given feedback straight after the movement (concurrent), asked to estimate performance, or given delayed feedback. Following a retention test it was found that even though concurrent feedback is an immediate indicator of success it was detrimental to learning because it may have blocked or interfered with information-processing activities leading to the learning of error-detection capabilities. Instead, delayed feedback was found to produce superior learning due to the promotion of better error-detection capabilities. As the movement used in this study was a simple laboratory task, the findings may not transfer to complex motor skills and needs to be investigated further.

Consideration of the skill level of the performer is typically the most appropriate way to determine the feedback schedule (Magill & Anderson, 2012). As skill level increases and task complexity decreases the use of augmented feedback can make it difficult for the performer to progress without developing a dependency on this information. On the other hand, when skill level is low and task complexity is high, the learner would likely need guidance from augmented feedback to find effective ways to improve performance. In a rare study in an applied setting with a complex movement pattern, Baudry et al. (2006) studied 18 gymnasts to determine if concurrent auditory feedback could be used to improve body alignment during the pommel horse circle. After two weeks of training the concurrent feedback back group were able to improve their body alignment by 2.3%. The findings from this study are similar to

Spinks and Smith (1994) who found that concurrent augmented feedback can have a powerful effect on learning complex sporting tasks. The rationale behind this is that there may be some kinematic information that is not naturally available to the athlete during the task. However, when feedback is given in real time the athlete is able to make feedback-based corrections leading to improved performance (Moran et al., 2012). Further, the concurrent feedback may also facilitate the direct link between desired outcomes and the athlete’s intrinsic information resulting in better performances in the long term as well (Swinnen, Lee, Verschueren, Serrien, & Bogaerds, 1997). Although, the movement used in this particular study was a cyclical movement and therefore the results may not translate to discrete skills like the swimming start.

## 2.13 Precision of Feedback Content

In addition to feedback scheduling, the precision of feedback should also be considered. The precision of feedback refers to manipulations that alter the accuracy of the error (Salmoni et al., 1984). Precision feedback can be provided in two ways; qualitative feedback or quantitative feedback or sometimes a combination of the two is used. A qualitative feedback statement (direction) usually refers to the quality of the performance, but not precise information about the outcome of the performance. A quantitative feedback statement (magnitude) provides precise information about the magnitude and direction of the response error (Reeve, Dornier, & Weeks, 1990). For example “long” (qualitative feedback) or “long 2 m” (quantitative feedback). When task performance is dependent on an external source of information, quantitative feedback facilitates performance (Reeve et al., 1990). Further, quantitative feedback has been shown to help learners perform more accurately, particularly during a complex sport specific skill (Phillips, Farrow, Ball, & Helmer, 2013). As this thesis is concerned with a complex skill like the swimming start, there are a number of theoretical issues associated with this type of feedback that should be considered.

Precise feedback can enhance learning (Phillips et al., 2013), but at the same time can cause temporary disruptions in performance (Gaudagnoli, Dornier, & Tandy, 1996; Gaudagnoli, Holcomb, & Davis, 2002). This is because precise feedback can cause the learner to make multiple mechanical changes, which can have a short-term negative effect on performance. For example, trying to change the mechanics of a swimming start during a race under pressure can degrade performance, but in the long-term this type of feedback can enhance learning and improve performance. Consequently, it is important to note that the positive changes in movement patterns may not be immediately evident in performance. It would appear from multiple studies that there is a period of time required to become 'comfortable' with changes that come from precise instruction (Barris, Farrow, & Davids, 2014; Baudry et al., 2006; Gaudagnoli et al., 1996). The immediate disruptions to performance are probably likely due to the changes in mechanics and the cognitive effort associated with these changes to a complex task.

If a learner is given too little precision, there may not be enough detail for them to adapt their next movement. On the other hand, if there is too much precision it can be harmful and cause the learner too much variation during the performance of the task. Therefore, many researchers suggest that feedback precision should be low during early practice and higher once the learner becomes more proficient (Salmoni et al., 1984). Reeve et al. (1990) examined 48 undergraduate students who performed an 80 cm movement task in 500 m.s$^{-1}$. After each trial the subjects were given quantitative feedback over either a narrow bandwidth (10 m.s$^{-1}$, more precise) or broader bandwidth (50 m.s$^{-1}$, less precise) in blocks of five before a no-feedback retention test. During the initial trials the narrow group had greater response errors due to the subjects overcorrecting the response as a result of the precise error statements provided. After a few trials (5) subjects were able to develop a better comprehension for the error statement and were then able to use the precise information. Given that the broader group received less relative frequency of feedback than the narrow group the broader group performed better during the no-feedback retention test. The results from this study demonstrate the usefulness of precise feedback to skill learning, although the link between learning and precise biomechanical feedback is currently not well represented in the literature.

The majority of feedback research has centred on the type and timing of the feedback provided, particularly when learning a complex sport skill. Moran et al. (2012) provided junior national tennis players precise information about their tennis serve speed. The results showed that providing accurate and precise augmented feedback of service speed significantly enhanced the learning process, with a large increase in speed compared to a no feedback control group. Similarly, Ford, Hodges, and Williams (2007) asked performers to kick a ball over a bar and examined the effect of providing erroneous visual feedback on the height that the ball reached above the bar. The results showed that even highly skilled players were able to benefit from this type of feedback by subsequently improving the outcome of ball height. This suggests that feedback is a useful tool to facilitate the exploration of different solutions to a complex task.

### 2.14 Biomechanical Feedback as a Form of Augmented Feedback

Providing kinematic feedback may be more appropriate to aid in skill learning especially when refining a complex motor skill. An example of this would be providing biomechanical feedback from video or split timing. Kinematic feedback augments intrinsic feedback by directing a learner's attention to the part/s of a task that is critical to performance (Young & Schmidt, 1992). This type of feedback also informs the learner directly about what is needed to improve a given movement.  Augmented kinematic feedback is often given for more complex movement tasks and can produce benefits in both performance and learning. The first study to produce performance improvements from augment kinematic feedback was English (1942) who reported that army recruits made remarkable improvement in shooting performance when provided feedback about the trigger pressure relative to that of an expert marksmen. Since then there have been multiple studies which have demonstrated performance benefits with the use of biomechanical feedback (Baudry, Leroy, Thouvarecq, & Choller, 2006; Gaudagnoli, Dornier, & Tandy, 1996; Hodges & Franks, 2008; Lai & Shea, 1999; Rucci & Tomporowski, 2010).

There is a clear link between biomechanical feedback, learning and performance (Abernethy et al., 2008). When designing a study which assesses this relationship between biomechanical feedback and skill acquisition, Abernethy et al. (2008) recommended a number of considerations for the selection of parameters utilised. These are (i) the variable selected for feedback must be a key variable for performance improvement; (ii) the variable must be able to be adopted or adjusted by the athlete, (iii) the system or device must be able to accurately and reliably measure the variable (s) that are selected (Phillips et al., 2013). Particularly when dealing with biomechanical feedback in a sport setting, the identification of key performance variables is typically completed through factor analysis, correlations or regression analysis (Ball, Best, & Wrigley, 2003). However, it is very unlikely that just one variable would act in isolation to impact performance of a particular skill (Abernethy et al., 2008). Most sport performance outcomes are both speed and accuracy based and require control of a number of degrees of freedom (Phillips et al., 2013). Another issue that can arise when working with complex motor skills is that feedback on one specific component may improve that aspect of movement, but at the same time may be detrimental to another aspect of the movement. Therefore, it is important that the coach and sport scientist prioritise the variable that would affect performance the most when designing a study or selecting a feedback parameter. This two-step process has been effectively demonstrated on a number of occasions (Arend & Higgins, 1976; Hodges & Franks, 2008; Weeks & Kordus, 1998).

There are a number of complex sport specific skill studies which have used kinematic feedback to improve performance. Rucci and Tomporowski (2010) investigated the use of video feedback with verbal attentional focus cues to improve the hang clean. They found the combinational use of kinematic feedback was effective in improving the start phase of the hang clean movement. However a video and verbal cue group did not improve performance over a verbal-only group. The researchers attributed this to the fact that some aspects of the hang clean movement may be better modulated by the way of verbal feedback. Hume and Soper (2003) also reviewed the visual and verbal feedback approach in rowing and found that this technique was effective in improving rowing technique. Therefore, highly skilled athletes, sports scientists and coaches should aim to provide accurate specific perceptual information that can guide the learner towards optimal movement patterns. An example of this would be biomechanical feedback in the form of either kinetic force information or kinematic information regarding movement.

### 2.15 Augmented Feedback and Swimming

Research utilising augmented feedback and complex swimming skills is scarce. Using the glide phase of the swimming start and a test-retest with retention design, Thow et al. (2012) examined 19 elite swimmers who were divided into three different feedback groups. Group one were only given video replay of their glide performances, group two received the same video replay and verbal feedback while group three were given video replay, verbal feedback and quantification of glide performance variables using the specifically designed “GlideCoach” software (Thow et al., 2012). GlideCoach provided information on knowledge of results and performance-related kinematic variables (initial velocity, average velocity and glide factor). The results showed that Group one and two improved glide performance after a month without further practice or intervention during the retention test, suggesting that GlideCoach offered feedback that was effective in improving the swimmers glide performance (Thow et al., 2012). The use of specialised software proved to be effective in this instance, however the content and precision of the feedback provided from the software was unclear. Hence, the final study of this thesis would aim to provide more evidence to support the use of augmented feedback for complex skill improvement in swimming.

In another study that utilised an intervention design with a complex swimming skill, Sanders (1995) investigated whether skilled performers can readily change their technique. Nine competitive Masters swimmers were taught to change their breaststroke technique using video and verbal feedback over 10 lessons of 45 minutes. The results demonstrated that considerable learning towards the desired movement pattern was established after the intervention period. However, the movement used in this study was cyclical and although there is evidence that video feedback was effective with a complex skill, the findings may not translate to other discrete skills such as starts or turns as there is less intrinsic feedback available to the performer. This further highlights the need to formulate a swimming specific study which examines the effect of biomechanical feedback on skill learning.

The final sections of literature review have established the importance of augmented feedback for skill learning. However, there is a clear gap in the literature particularly concerning the scheduling and use of biomechanical feedback for skill learning. The current body of literature concerning the delivery of feedback for skill learning is limited to laboratory based tasked and the link from these findings to complex skill learning is unclear. Hence, this thesis would attempt to expand on previous studies by investigating how biomechanical feedback can be best utilised for skill improvement in a swimming start.

## 2.16 Conclusion

The importance of the swimming start has been highlighted in this literature review, with clear gaps in knowledge that need to be addressed, particularly with regards to the new kick-start technique. Resistance in swimming has also been detailed and identified as being a major determinant for start performance, which places emphasis on the necessity for research focused on reducing resistance and improving swimming start performance. Information about the reduction in resistance combined with research on the delivery of kinematic feedback would allow coaches to specifically train their athletes to improved start performance.

# Chapter 3: Reliability of an Instrumented Start Block Analysis System

## Chapter 3.0 Reliability of an Instrumented Start Block Analysis System

*From:* **Tor, E.,** Pease, D., & Ball, K. (2015). The reliability of an instrumented start block analysis system. *Journal of Applied Biomechanics, 31*, 62-67.


### 3.1 Abstract

The swimming start is highly influential to overall competition performance. However, it is paramount to develop reliable methods to perform accurate biomechanical analysis of start performance for training and research. The Wetplate Analysis System is a custom-made force plate system developed by the Australian Institute of Sport – Aquatic Testing, Training and Research Unit (AIS ATTRU). This sophisticated system combines both force data and 2D digitisation to measure a number of kinetic and kinematic parameter values in an attempt to evaluate start performance. Fourteen elite swimmers performed two maximal effort dives (performance was defined as time from start signal to 15 m) over two separate testing sessions. Intra-class correlation coefficients (ICC) were used to determine each parameter's reliability. The kinetic parameters all had ICC greater than 0.9 except time of peak vertical force (0.742). This may have been due to variations in movement initiation after the starting signal between trials. The kinematic and time parameters also had ICC greater than 0.9 apart from for time of maximum depth (0.719). This parameter was lower due to the swimmers varying their depth between trials. Based on the high ICC scores for all parameters, the Wetplate Analysis System is suitable for biomechanical analysis of swimming starts.


### 3.2 Introduction

Swimming starts contribute highly to overall competition performance, in fact they have been shown to contribute anywhere between 0.8 to 26.1% of total race time (Lyttle & Benjanuvatra, 2005). Therefore, it is important that reliable methods to perform accurate biomechanical analysis of start performance are developed for training and research for aquatics. The swimming start is typically broken into the on-block, flight and underwater phases (Vantorre, Seifert, Fernandes et al., 2010). Each of these phases has been previously assessed by multiple studies which have explored a number of different biomechanical aspects of the swimming start using various systems (Biel, Fischer, & Kibele, 2010; Cosser, Slawson, Justham, Conway, & West, 2010; Honda, Sinclair, Mason et al., 2010; Nomura, Takeda, & Takagi, 2010; Slawson, Conway, Cosser et al., 2011; Thow, Naemi, & Sanders, 2012; Vantorre, Seifert, Fernandes et al., 2010).

One way to measure start performance is to utilise a force plate system which also incorporates vision of the swimmer's performance that allows for 2D manual digitising. Only a handful of studies have used such systems to combine video, kinematic and kinetic measures (Fischer & Kibele, 2014), while even fewer studies have utilised an analysis system that emulate the FINA approved Omega OSB11 starting block (Honda, Sinclair, Mason et al., 2010; Slawson, Chakravorti, Conway, Cosser, & West, 2012). Such systems have the ability to collect accurate data that can be used to identify meaningful changes to a swimmers' start technique. In a high performance environment such systems are invaluable to improving a swimmer's start performance. However, few studies have detailed the reliability of the measured values derived from such systems.

As technology advances there have been more sophisticated biomechanical systems developed that assess swimming start performance. Currently, there are no such systems available commercially (but there would be in the near future), hence the AIS ATTRU has developed an analysis system known as Wetplate which has been successfully utilised in a number of research studies (Honda, Sinclair, Mason et al., 2010, 2012; McCabe, Mason, & Fowlie, 2012;

Tor, Pease, & Ball, 2014). The reliability of this system has been determined previously, however the results have not yet been published.

Many researchers have utilised the Wetplate Analysis System to study start performance (Honda, Sinclair, Mason et al., 2010, 2012; McCabe, Mason, & Fowlie, 2012; Tor, Pease, & Ball, 2014). Wetplate is a custom built force plate system which incorporates an instrumented start block with the same dimensions as the Omega OSB11, a series of high speed cameras and a timing system known as Swimtrak. The purpose of developing Wetplate was to accelerate the learning and refining of a swimmers' start performance (Mason, Mackintosh, & Pease, 2012). This system can also provide coaches with immediate feedback regarding kinematic and kinetic parameters.

To analyse kinematic measures of dive start performance, researchers have previously relied on 2D manual digitising from video footage (Barlow, Halaki, Stuelcken et al., 2014; Nomura, Takeda, & Takagi, 2010; Takeda, Takagi, & Tsubakimoto, 2013; Vantorre, Seifert, Fernandes et al., 2010) In addition, kinetic parameters were typically measured using instrumented start platforms made from modified force plates (Fischer & Kibele, 2014; Honda et al., 2010; Slawson et al., 2012; Tor, Pease, et al., 2014). Therefore, with the development and use of Wetplate coaches and sport scientists are able to utilise the high-speed video footage for qualitative feedback together with the kinematic and kinetic parameters for immediate quantitative feedback.

Wetplate is one of the first systems of its kind in the world. It has been used successfully on multiple occasions for research and athlete servicing purposes; however the reliability of the parameter values it produces has not been formally established. Although this system is unique, it has been used as a prototype for similar systems which would become commercially available. Therefore, the findings from this study may be generalised to more than just the Wetplate Analysis System. In order to assess the day-to-day variation in measurement, the aim of this study was to determine the inter-trial reliability of the Wetplate Analysis System. Reliability analysis was conducted for all parameters measured utilising a sample of elite swimmers.

## 3.3 Methods

### 3.3.1 Subjects

This study was approved by the Australian Institute of Sport (AIS) Performance Research Ethics Committee. Fourteen swimmers (11 male, 3 female, 19 ± 1 y) were recruited from the AIS and other Australian state institute swimming programs. All swimmers were considered highly proficient, with two Olympic representatives, two World Championship representatives and eight Australian national open finalists. All swimmers were able to qualify for the national championships in the 100 m freestyle (53.10 s for males, 59.00 s for females) and had at least 5 years of competitive swimming experience at the national level.

### 3.3.2 Procedure

Each swimmer was tested using a test-retest design. Prior to testing, each swimmer performed their usual pre-race warm-up, which was consistent for both test sessions. Swimmers were tested on consecutive days, performing two maximal effort dives starts (to 15 m) with two minutes of rest in between each trial. A detailed list of parameters measured by Wetplate is described in Appendix I.

### 3.3.3 Equipment

The Wetplate Analysis System was used to collect all data in this study (Figure 6). The starting block was angled at ten degrees downward toward the pool and comprised of a Kistler force platform (Z20314, Winterthur, Switzerland) and two Kistler tri-axial transducers (9601A) placed in a bar at the front of the starting block to measure grab force. All force data is presented in the global coordinate system with calculations embedded in the Wetplate Analysis System to account for the 10 degree angle of the force plates. The rear foot contribution is measured using an instrumented incline plate with four Kistler tri-axial transducers (9251A). All force data were collected at 500 Hz and filtered using a 10 Hz low pass digital Butterworth filter.

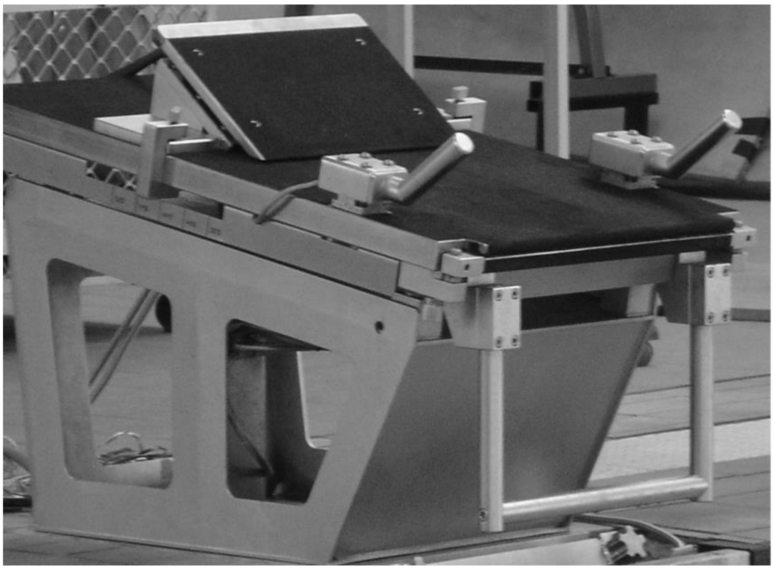


**Figure 6 Wetplate Analysis System - Instrumented Starting Block**

The Wetplate system also incorporated four calibrated high-speed gigabit Ethernet (GigE) cameras (Pulnix, TMC-6740GE) that were calibrated for specific locations in the pool, collecting at 100 frames per second. The cameras were positioned normal to the direction of the subject's movement (Figure 7). One camera was positioned 1.5 m above the water and 2 m out from the start wall to capture the start signal (led light) and entry into the water, while the other three cameras were positioned underwater at 1.6 m, 5.6 m and 12.8 m out from the start wall and 1.7 m below the surface of the water to capture the swimmer's underwater and above water motion from 0 m to 15 m.

The start signal was integrated into the analysis system and acts as a trigger for data collection from all force plates and cameras. Intermediate split times were obtained from a separate parallel system known as Swimtrak. This system is also proprietary software developed by the AIS ATTRU. Swimtrak comprises of eight time synchronized analogue video cameras (Samsung, SCC-C4301P) located perpendicular to the swimmer's plane of motion at 0 m, 2.5m, 5 m, 7.5 m, 10 m, 15 m, 20 m and 25 m approximately 5 m above the surface of the pool. The swimmer's times from the start signal were recorded as the centre of the swimmer's head passes through lines drawn on the image from each camera that were perpendicular to the side of the pool, before being manually inputted into Wetplate.

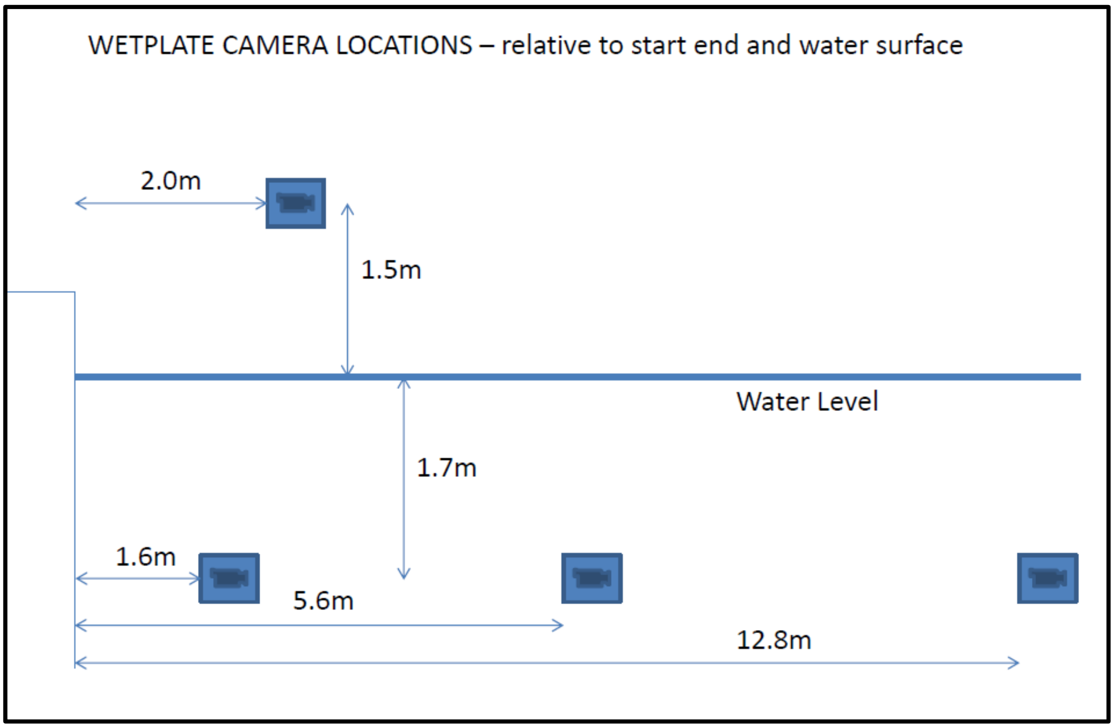



**Figure 7 Wetplate Analysis System camera set up**

### 3.3.4 Statistical Analysis

Reliability of the Wetplate Analysis System was assessed using intra-class correlation coefficients (ICC) (formula 3,4). ICC was conducted across each of the four trials collected for each subject (each trial was treated as an individual data point). A separate analysis was conducted for each of the parameters measured by the system. The ICC classifications of Fleiss (1986) (less than 0.4 was poor, between 0.4 and 0.75 was fair to good, and greater than 0.75 is excellent) were used to describe the range of ICC values. 95% confidence intervals were also reported alongside these values in Table 3. Similar reliability analysis has previously been described in Atkinson and Nevill (1998) and Weir (2005). Statistical analysis was conducted using SPSS statistical software (version 19.0, SPSS, Chicago, IL).

## 3.4 Results

The ICC for each parameter, 95% confidence intervals and reliability classification have been reported (Table 1). All parameters returned an ICC above 0.9 which, according to the classifications of Fleiss (1986), indicated a high (excellent) inter trial reliability. The only exceptions to this were for time of peak vertical force (0.742) and time of maximum depth (0.719) which was classified as medium (good) reliability.

**Table 1 The reliability of each parameter measured by the Wetplate Analysis System.**

| Parameter | ICC | 95% Confidence Interval | Reliability |
|---|---|---|---|
| Mass (Kg) | 0.999 | 0.997 ± 0.999 | Excellent |
| Mass (N) | 0.999 | 0.997 ± 0.999 | Excellent |
| Block Time (s) | 0.974 | 0.943 ± 0.990 | Excellent |
| Take-off Horizontal Velocity ($m \cdot s^{-1}$) | 0.988 | 0.976 ± 0.996 | Excellent |
| Take-off Vertical Velocity ($m \cdot s^{-1}$) | 0.980 | 0.956 ± 0.992 | Excellent |
| Dive Angle (°) | 0.981 | 0.959 ± 0.993 | Excellent |
| Average Acceleration ($m \cdot s^{-2}$) | 0.987 | 0.972 ± 0.995 | Excellent |
| Average Power per kg (w/kg) | 0.987 | 0.972 ± 0.995 | Excellent |
| Peak Power per kg (W/kg) | 0.975 | 0.946 ± 0.991 | Excellent |
| Peak Power (BW) | 0.987 | 0.971 ± 0.995 | Excellent |
| Work (J) | 0.987 | 0.971 ± 0.995 | Excellent |
| Peak Vertical Force (BW) | 0.959 | 0.911 ± 0.985 | Excellent |
| Time of Peak Vertical Force (s) | 0.742 | 0.448 ± 0.902 | Good |
| Peak Horizontal Force (BW) | 0.990 | 0.978 ± 0.996 | Excellent |
| Time of Peak Horizontal Force (s) | 0.972 | 0.940 ± 0.990 | Excellent |
| Peak Grab Force (BW) | 0.992 | 0.982 ± 0.997 | Excellent |
| Time of Peak Grab Force (s) | 0.956 | 0.905 ± 0.984 | Excellent |
| Peak Kick Plate Force (BW) | 0.973 | 0.941 ± 0.990 | Excellent |
| Time of Peak Kick Plate Force (s) | 0.938 | 0.864 ± 0.977 | Excellent |
| Time Head Enters (s) | 0.979 | 0.954 ± 0.992 | Excellent |
| Time in Air (s) | 0.978 | 0.951 ± 0.992 | Excellent |
| Entry Distance (m) | 0.979 | 0.955 ± 0.992 | Excellent |
| Entry Hold Diameter (m) | 0.927 | 0.842 ± 0.973 | Excellent |
| CoG Angle of Entry (°) | 0.981 | 0.959 ± 0.993 | Excellent |
| Entry Velocity ($m \cdot s^{-1}$) | 0.970 | 0.934 ± 0.989 | Excellent |
| Time of First Kick (s) | 0.958 | 0.907 ± 0.984 | Excellent |
| Maximum Depth (m) | 0.881 | 0.737 ± 0.955 | Excellent |
| Distance of Maximum Depth (m) | 0.822 | 0.612 ± 0.933 | Excellent |
| Time of Maximum Depth (s) | 0.719 | 0.386 ± 0.895 | Good |
| Time Underwater in Descent (s) | 0.766 | 0.989 ± 0.912 | Excellent |
| Time Underwater in Ascent (s) | 0.957 | 0.906 ± 0.984 | Excellent |
| Total Time Underwater (s) | 0.951 | 0.892 ± 0.981 | Excellent |
| Breakout Time (s) | 0.949 | 0.889 ± 0.981 | Excellent |
| Breakout Distance (m) | 0.949 | 0.889 ± 0.981 | Excellent |
| Time to 5 m (s) | 0.984 | 0.965 ± 0.994 | Excellent |
| Average Velocity 0-5 m ($m \cdot s^{-1}$) | 0.981 | 0.959 ± 0.993 | Excellent |
| Time to 7.5 m (s) | 0.987 | 0.971 ± 0.995 | Excellent |
| Average Velocity 5-7.5 m ($m \cdot s^{-1}$) | 0.968 | 0.930 ± 0.988 | Excellent |
| Time to 10 m (s) | 0.983 | 0.963 ± 0.994 | Excellent |
| Average Velocity 7.5-10 m ($m \cdot s^{-1}$) | 0.959 | 0.912 ± 0.985 | Excellent |
| Time to 15 m (s) | 0.988 | 0.973 ± 0.995 | Excellent |
| Average Velocity 10-15 m ($m \cdot s^{-1}$) | 0.965 | 0.924 ± 0.987 | Excellent |
| Underwater Velocity ($m \cdot s^{-1}$) | 0.958 | 0.909 ± 0.984 | Excellent |

### 3.5 Discussion

While each of the individual components of the Wetplate Analysis System (high-speed cameras, force plate, 2D digitising) have been evaluated for reliability, the reliability of the entire Wetplate system has not been published until now. Hence, the aim of this study was to assess the reliability of all the parameters measured by the Wetplate Analysis System. To measure reliability in this study ICC and 95% confidence intervals were used.

All of the kinetic parameters assessed by the Wetplate force plate returned 'excellent' reliability measures. The only force measurement value that was not classified as reliable was the time of peak vertical force (0.742). While this ICC still indicates 'good' reliability, the most likely reason for this value being lower than the other force parameters is because of the natural variability in timing that occurs even for elite swimmers. Time of peak vertical force is highly dependent on the swimmer's rate of force generation during the on-block phase and this may vary from trial to trial, depending on when movement is initiated after the start signal, thus leading to a slightly decreased intra-trial reproducibility. Despite this, the results of this study have shown that all of the kinetic parameters measured by Wetplate are reliable.

Analogous to the kinetic parameters, the kinematic parameters measured by Wetplate were also found to be highly reliable. All of the kinematic and time parameters displayed an ICC of greater than 0.9 except for the time of maximum depth (0.719). This parameter was manually digitised immediately following each trial. Even though the same person digitised all of the trials in this study, the reliability was still to some extent less than that of the other digitised points. Similar to the time of peak vertical force, this may be caused by this parameter being more variable from one trial to another regardless of the swimmers' skill level. Further, the time of maximum depth was used to calculate a number of other parameters such as time underwater in descent and time underwater in ascent. These parameters proved to be highly reliable. Consequently the lower reproducibility of the time of maximum depth did not affect the overall reliability of the kinematic measure from Wetplate.

The aim of this study was to assess the reliability of a customised force plate known as the Wetplate Analysis System. This system has been used on multiple occasions to evaluate swimming start performance. However the system's reliability has not previously been documented. The results from this study demonstrate that the Wetplate Analysis System is highly reliable for all of the parameters measured. All parameters displayed ICC greater than 0.9 except for the time of maximum depth and the time of peak vertical force. Therefore, the Wetplate system proved to be reliable and a highly useful tool for assessing swimming starts. Finally, as the Wetplate Analysis System has been used as a prototype, the findings from this study can be referred to when using similar commercially available start analysis systems.

# Chapter 4: Characteristics of an Elite Swimming Start

## Chapter 4.0 Characteristics of an Elite Swimming Start

*From:* Tor, E., Pease, D., & Ball, K. (2014). *Characteristics of an elite swimming start*. Paper presented at the Biomechanics and Medicine in Swimming Conference 2014, Canberra. 257-263

### 4.1 Abstract

The implementation of a new start block to competitive swimming has resulted in a new start technique being utilized. While aspects of this new technique have been previously assessed, there is a need to characterize technical factors in the new swim start and determine if differences exist between male and female athletes as well as between strokes. The aims of this study were to investigate how elite swimmers of both genders use the new start block, compare males and females and freestyle and butterfly start performances. Thirty-nine start parameters were calculated for 52 starts from trials collected by the Wetplate Analysis System and Swimtrak system at the Australian Institute of Sport. Subjects were all Australian Olympic or World Championship representatives. Descriptive statistics were calculated on a group basis before parameters were split into; above water and underwater phases for further analysis. Independent *t*-tests and Cohen's effect sizes were then calculated to compare groups and strokes. When examining the sub-phases of the start it was found that 11% (0.74 s) was spent in the on block phase, 5% (0.30 s) in the flight phase, 56% (3.69 s) in the underwater phase and 28% (1.81 s) free swimming once the athlete had resurfaced. Males produced significantly larger take-off horizontal velocity ($p < 0.001$, Large), peak horizontal force ($p < 0.001$, Large) and were also able to produce faster underwater velocities for all segments. Males also travelled significantly deeper ($p < 0.001$, Large). These findings resulted in males having significantly faster start performances than females ($p < 0.01$, Large); on average they were 0.95 s faster to 15 m. When comparing different strokes, butterfly swimmers had a significantly deeper

maximum depth (p = 0.01, Large) and breakout distance ($p < 0.001$, Large) than freestylers, but there was no significant difference in overall start performance ($p = 0.74$, Small). The results from this study were novel and characterized how elite swimmers utilized the new start block and kick-start technique. The importance of the underwater phase was clearly highlighted as swimmers spent the longest time in this phase. The results also showed that there were clear variances in start performance between male and female athletes due to males being able to generate greater force and velocity in the early phases of the start which translate into faster overall start performances. There were also differences present for underwater parameters when comparing butterfly and freestyle, however these differences do not result in differences in time to 15 m.

### 4.2 Introduction

In competitive swimming, the start has been strongly linked to overall performance (Cossor & Mason, 2001), The swimming start can contribute between 0.8-26.1% of total race time depending on the distance (Lyttle & Benjanuvatra, 2005), with the percentage contribution increasing as the distance of the race becomes shorter (Hay, 1986). The swimming start phase of a race is defined as the time from the starting signal to when the centre of the swimmer's head reaches 15 m (Cossor & Mason, 2001). The start as a whole is typically broken into three sub-phases: the on-block, flight and underwater phases. The percentage time contribution of each sub-phase is approximately 11%, 5% and 84% respectively (Slawson, Conway, Cosser, Chakravorti, & West, 2013). The on-block phase is described as the time from the starting signal to when the swimmer leaves the block while the flight phase is the time from when the swimmer leaves the block to when the swimmer enters the water. The last and longest phase of the start is the underwater phase and is the time from when the swimmer enters the water to when the swimmer resurfaces to begin free swimming. The free-swimming time is defined as the time following the underwater phase from breakout to 15 m.

Following the Beijing Olympics in 2008 a new starting block was introduced to international competition. The Omega OSB11 starting block has an adjustable kick plate, footrest or back plate fixed at 30° which can be moved to five different locations (35 mm intervals) along the length of the starting platform which is also angled at 10° to the horizontal. As a result of the introduction of these blocks a different starting technique called the "kick-start" has been developed and utilised by most elite swimmers during competition. Multiple research studies have found that swimmers can gain an added advantage using this new technique (Honda et al., 2010; Takeda et al., 2013). This is mainly due to an increase in horizontal velocity with the added contribution of the increased force that is able to be produced by the rear leg (Honda et al., 2010).

There have been many previous start studies that have compared different start techniques (Blanksby et al., 2002), or evaluated different elements of the start such as foot placement (Takeda et al., 2013), entry angle (Groves & Roberts, 1972) and starting position (Honda et al., 2012). Although these studies have used elite/sub-elite subjects the groups they used were mixed and comparisons between genders were not made. Cosser and Mason (2001) did separate their analysis into male and female groups, however they did not make comparisons between genders. Furthermore, Seifert et al. (2010), Vantorre et al. (2010), Breed et al. (2000), Kirner et al. (1989) examined start performance based only on low-to moderate numbers of single gender subjects. There is obvious strength, performance and technical differences present for males compared to female swimmers so combining genders in the same analysis may not be appropriate, as differences might exist in how velocity is developed.

The same observations can be made when comparing start performances for different strokes. There are even fewer studies that have combined different strokes in their study design. Only two known studies have compared the differences between freestyle and butterfly starts. (Strojnik, Strumbelj, & Bednarik, 1998) found small differences in the flight phase of the start, while Whitten (1997) found that butterfly swimmers travelled deeper during the underwater phase. Although, these studies compared the differences between strokes using a grab start technique. Given that the grab start has been superseded by the kick-start, the findings from these studies may not be relevant to techniques currently used in competition.

This study was the first to compare start performances and specific start parameters between male and female using elite swimmers and the new kick-start technique. The aims of this study were to characterise the swim start of elite swimmers using the new Omega OSB11 starting block and to make comparisons between gender and different strokes based on overall start performance.

**4.3 Methods**

Retrospective data was utilised in this study to determine the characteristics of the technique elite swimmers adopt during the kick-start using the Omega OSB11 starting block. Ethical approval was obtained from the Ethics Committee of The Australian Institute of Sport. The trials were selected from a database of start performances collected by the Australian Institute of Sport - Aquatic Testing, Training and Research Unit (AIS ATTRU). These trials were then filtered to include trials from able-bodied subjects wearing textile training swim wear (eliminating any trials where swimmers wore the now illegal swimsuits) who had made at least one senior Australian national swimming team (Olympics and World Championships) and specialised in either freestyle or butterfly. Once the data was filtered there were a total of 52 trials (29 male, 23 female, aged 22 ± 0.5 y) included in the study (52 swimmers, 1 trial per swimmer). Of these trials 39 swimmers were Olympians (30 Olympic Medallists) and 14 World Championship representatives (11 World Championship Medallists). Further, 39 were freestyle swimmers and 13 were butterfly swimmers. The Wetplate Analysis System and Swimtrak Timing System were used to collect all data in this study (Mason et al., 2012).

Descriptive statistics were calculated for each parameter on a group basis then data were split into above - water parameters (parameters that occurred before the swimmer entered the water) and underwater parameters (the remaining parameters that occurred after the swimmer entered the water) (Table 2). The Kolmogorov - Smirnov test confirmed all parameters were normally distributed ($p > 0.05$). Independent *t*-tests were then used to make comparisons between gender and the strokes using the smaller parameter groupings. Differences in performance were also made using independent *t*-tests between gender and the different strokes. Effect sizes were then calculated using Cohen's (*d*) to determine if the differences between each group were substantive (Cohen, 1988). The scale used to determine the size of the effect was 0.2, 0.5, 0.8; small, medium large respectively. All statistics were computed using SPSS software (version 19.0, SPSS, Chicago, IL).

**4.4 Results**

The mean percentage contribution for each phase of the start was calculated (Table 3). 11% (0.74 s) spent in the on-block phase, 5% (0.30 s) in the flight phase, 56% (3.69 s) in the underwater phase and 28% (1.81 s) free swimming. The mean percent contributions of each start phase were also calculated for each gender; males spent 12% (0.72 s) in the on-block phase, 5% (0.29 s) in the flight phase, 61% (3.72 s) in the underwater phase and 23% (1.39 s) free swimming. For females, 11% (0.77 s) was spent in the on-block phase, 4.1% (0.29 s) in the flight phase, 51.9% (3.67 s) in the underwater phase and 33.1% (2.34 s) free swimming.

A comparison between male and female showed there was a significant difference between overall performance time to 15 m with males 0.95 s faster than females ($p < 0.001$, Large) (*p*-value, effect size). This was due to males producing significantly larger take-off horizontal velocity (0.52 $m \cdot s^{-1}$, $p < 0.001$, Large), peak horizontal force (0.22 BW, $p < 0.001$, Large) and were also able to produce faster underwater velocities for all segments than females (Table 4). Males also travelled significantly deeper (0.20 m, $p < 0.001$, Large). For the underwater parameters there were significant differences in all average velocities and split times, horizontal distance of max depth of head (0.08 m, $p = 0.08$, Large), underwater velocity (0.27 $m \cdot s^{-1}$, $p < 0.001$, Large) and breakout distance (1.33 m, $p = 0.02$, Small)  (Table 5).

When differences between freestyle and butterfly were examined, there were no significant differences between any of the above-water parameters (Table 6). For the underwater parameters there were nine significant differences (Table 7).  The butterfly swimmers had a significantly deeper max depth (0.21 m, $p = 0.01$, Large) that was further away from the start blocks (0.82 m, $p < 0.01$, Large), spent more time underwater (1.10 s, $p < 0.00$, Large), had a higher underwater velocity (0.12 $m \cdot s^{-1}$, $p = 0.02$, Medium) and a longer breakout distance (2.24 m, $p < 0.00$, Large) than the freestyle swimmers. The medium effect sizes found for take-off vertical velocity, time in the air, dive angle and entry hole diameter further suggest that even though there was no statistical significance there were some differences which may account for the difference in underwater parameters between strokes.

**Table 2 Full descriptive statistic summary**

| Parameter | Mean and SD |
|---|---|
| Block Time (s) | 0.74 ± 0.05 |
| Take-off Horizontal Velocity ($m \cdot s^{-1}$) | 4.62 ± 0.31 |
| Take-off Vertical Velocity ($m \cdot s^{-1}$) | -1.25 ± 0.42 |
| Time in the air (s) | 0.29 ± 0.05 |
| Average Acceleration ($m \cdot s^{-2}$) | 6.26 ± 0.74 |
| CoG Angle of Entry (degrees) | 47.0 ± 2.2 |
| Dive Angle (degrees) | -15.14 ± 4.93 |
| Entry Distance (m) | 2.82 ± 0.02 |
| Entry Hole Diameter (m) | 0.65 ± 0.02 |
| Entry Velocity ($m \cdot s^{-1}$) | 6.79 ± 0.22 |
| Head Entry Time (s) | 1.04 ± 0.05 |
| Peak Footplate Force (N) | 1.55 ± 0.28 |
| Peak Grab Force (N) | 0.88 ± 0.22 |
| Peak Horizontal Force (N) | 1.24 ± 0.19 |
| Peak Vertical Force (N) | 1.29 ± 0.19 |
| Peak Power Per Kilogram (w/kg) | 56.41 ± 10.36 |
| Time of Full Submersion (s) | 1.34 ± 0.05 |
| Time After Entry of First Kick (s) | 0.44 ± 0.22 |
| Time of First Kick (s) | 2.04 ± 0.24 |
| Horizontal Distance of Max depth (m) | 6.06 ± 0.97 |
| Max Depth of Head (m) | -0.97 ± 0.23 |
| Time at Max Depth (s) | 1.94 ± 0.41 |
| Time Underwater in Accent (s) | 2.79 ± 0.73 |
| Time Underwater in Descent (s) | 0.90 ± 0.41 |
| Total Time Underwater (s) | 3.70 ± 0.97 |
| Underwater Velocity ($m \cdot s^{-1}$) | 2.38 ± 0.21 |
| Breakout Distance (m) | 11.50 ± 1.97 |
| Time of Surfacing (s) | 4.73 ± 0.97 |
| Time to 5 m (s) | 1.56 ± 0.12 |
| Avg. Velocity 0-5 m ($m \cdot s^{-1}$) | 3.22 ± 0.21 |
| Time to 7.5 m (s) | 2.58 ± 0.25 |
| Avg. Velocity 5-7.5 m ($m \cdot s^{-1}$) | 2.49 ± 0.32 |
| Time to 10 m (s) | 3.87 ± 0.35 |
| Avg. Velocity 7.5 -10 m ($m \cdot s^{-1}$) | 1.95 ± 0.17 |
| Time to 15 m (s) | 6.54 ± 0.53 |
| Avg. Velocity 10-15 m ($m \cdot s^{-1}$) | 1.88 ± 0.14 |

**Table 3 Mean time and percentage time contribution for each sub-phase of the swimming start.**

| Start Sub-Phase | Time (s) | Percentage Contribution (%) |
|---|---|---|
| On Block Phase | 0.74 | 11 |
| Flight Phase | 0.30 | 5 |
| Underwater Phase | 3.69 | 56 |
| Free Swim | 1.81 | 28 |

**Table 4 Above - water parameter comparisons between male and female**

| Parameter | Male | Female | Difference in Mean | P Value | Effect Size |
|---|---|---|---|---|---|
| Block Time (s) | 0.72 ± 0.04 | 0.77 ± 0.05 | 0.05 | 0.00* | Large |
| Take-off Horizontal Velocity ($m.s^{-1}$) | 4.85 ± 0.17 | 4.33 ± 0.19 | 0.52 | 0.00* | Large |
| Take-off Vertical Velocity ($m·s^{-1}$) | -1.19 ± 0.46 | -1.32 ± 0.36 | 0.13 | 0.25 | Small |
| Time in the air (s) | 0.30 ± 0.05 | 0.29 ± 0.04 | 0.01 | 0.35 | Small |
| Average Acceleration ($m·s^{-2}$) | 6.76 ± 0.49 | 5.63 ± 0.47 | 1.13 | 0.00* | Large |
| CoG Angle of Entry (degrees) | 45.57 ± 1.56 | 48.81 ± 1.58 | 3.24 | 0.00* | Large |
| Dive Angle (degrees) | -13.71 ± 5.01 | -16.93 ± 4.23 | 3.22 | 0.02* | Medium |
| Entry Distance (m) | 2.93 ± 0.16 | 2.67 ± 0.15 | 0.26 | 0.00* | Large |
| Entry Hole Diameter (m) | 0.60 ± 0.15 | 0.72 ± 0.17 | 0.12 | 0.01* | Large |
| Entry Velocity ($m·s^{-1}$) | 6.94 ± 0.11 | 6.59 ± 0.14 | 0.35 | 0.00* | Large |
| Head Entry Time (s) | 1.01 ± 0.05 | 1.06 ± 0.05 | 0.05 | 0.01* | Large |
| Peak Footplate Force (N) | 1.70 ± 0.26 | 1.36 ± 0.18 | 0.34 | 0.00* | Large |
| Peak Grab Force (N) | 0.96 ± 0.20 | 0.77 ± 0.20 | 0.19 | 0.00* | Large |
| Peak Horizontal Force (N) | 1.33 ± 0.15 | 1.11 ± 0.15 | 0.22 | 0.00* | Large |
| Peak Vertical Force (N) | 1.36 ± 0.21 | 1.21 ± 0.14 | 0.15 | 0.00* | Large |
| Peak Power per Kilogram (w) | 62.56 ± 8.47 | 48.65 ± 6.68 | 13.91 | 0.00* | Large |

*Significant for $p < 0.05$

**Table 5 Underwater parameter comparisons between male and female**

| Parameter | Male | Female | Difference in Mean | P Value | Effect Size |
|---|---|---|---|---|---|
| Time of Full Submersion (s) | 1.34 ± 0.05 | 1.35 ± 0.06 | 0.01 | 0.29 | Small |
| Time After Entry of First Kick (s) | 0.42 ± 0.21 | 0.46 ± 0.24 | 0.04 | 0.61 | Small |
| Time of First Kick (s) | 2.01 ± 0.21 | 2.08 ± 0.28 | 0.07 | 0.36 | Small |
| Horizontal Distance of Max depth (m) | 6.29 ± 0.65 | 5.78 ± 1.22 | 0.51 | 0.08 | Large |
| Max Depth of Head (m) | -1.05 ± 0.20 | -0.85 ± 0.21 | 0.20 | 0.00* | Large |
| Time at Max Depth (s) | 1.88 ± 0.25 | 2.01 ± 0.55 | 0.13 | 0.29 | Small |
| Time Underwater in Accent (s) | 2.85 ± 0.70 | 2.72 ± 0.77 | 0.13 | 0.54 | Small |
| Time Underwater in Descent (s) | 0.86 ± 0.24 | 0.95 ± 0.55 | 0.09 | 0.45 | Small |
| Total Time Underwater (s) | 3.71 ± 0.86 | 3.68 ± 1.11 | 0.03 | 0.91 | Small |
| Underwater Velocity ($m \cdot s^{-1}$) | 2.50 ± 0.17 | 2.23 ± 0.13 | 0.27 | 0.00* | Large |
| Breakout Distance (m) | 12.10 ± 1.70 | 10.77 ± 2.06 | 1.33 | 0.02* | Small |
| Time of Surfacing(s) | 4.73 ± 0.87 | 4.73 ± 1.10 | - | 0.98 | Medium |
| Time to 5 m (s) | 1.47 ± 0.05 | 1.67 ± 0.08 | 0.20 | 0.00* | Large |
| Avg. Velocity 0-5 m ($m \cdot s^{-1}$) | 3.40 ± 0.12 | 3.01 ± 0.15 | 0.39 | 0.00* | Large |
| Time to 7.5 m (s) | 2.39 ± 0.08 | 2.82 ± 0.15 | 0.43 | 0.00* | Large |
| Avg. Velocity 5-7.5 m ($m \cdot s^{-1}$) | 2.74 ± 0.15 | 2.17 ± 0.18 | 0.57 | 0.00* | Large |
| Time to 10 m (s) | 3.59 ± 0.10 | 4.22 ± 0.19 | 0.63 | 0.00* | Large |
| Avg. Velocity 7.5 -10 m ($m \cdot s^{-1}$) | 2.08 ± 0.10 | 1.79 ± 0.07 | 0.29 | 0.00* | Large |
| Time to 15 m (s) | 6.12 ± 0.16 | 7.07 ± 0.28 | 0.95 | 0.00* | Large |
| Avg. Velocity 10-15 m ($m \cdot s^{-1}$) | 1.98 ± 0.08 | 1.76 ± 0.10 | 0.22 | 0.00* | Large |

*Significant for $p < 0.05$

**Table 6 Above - water parameter comparisons for freestyle and butterfly**

| Parameter | Freestyle | Butterfly | Difference in Mean | P Value | Effect Size |
|---|---|---|---|---|---|
| Block Time (s) | 0.75 ± 0.05 | 0.73 ± 0.05 | 0.02 | 0.29 | Medium |
| Take-off Horizontal Velocity ($m \cdot s^{-1}$) | 4.63 ± 0.32 | 4.59 ± 0.30 | 0.04 | 0.64 | Small |
| Take-off Vertical Velocity ($m \cdot s^{-1}$) | -1.31 ± 0.40 | -1.08 ± 0.44 | 0.23 | 0.11 | Medium |
| Time in the air (s) | 0.29 ± 0.05 | 0.31 ± 0.04 | 0.02 | 0.10 | Medium |
| Average Acceleration ($m \cdot s^{-2}$) | 6.24 ± 0.76 | 6.33 ± 0.68 | 0.09 | 0.68 | Small |
| CoG Angle of Entry (degrees) | 46.96 ± 2.32 | 47.14 ± 2.08 | 0.18 | 0.80 | Small |
| Dive Angle (degrees) | -15.75 ± 4.65 | -13.31 ± 5.49 | 2.44 | 0.17 | Medium |
| Entry Distance (m) | 2.81 ± 0.20 | 2.84 ±0.19 | 0.03 | 0.68 | Small |
| Entry Hole Diameter (m) | 0.67 ±0.17 | 0.59 ± 0.13 | 0.08 | 0.07 | Medium |
| Entry Velocity ($m \cdot s^{-1}$) | 6.80 ± 0.22 | 6.76 ± 0.21 | 0.04 | 0.50 | Small |
| Head Entry Time (s) | 1.04 ± 0.05 | 1.04 ± 0.05 | - | 0.78 | Small |
| Peak Footplate Force (N) | 1.54 ± 0.29 | 1.58 ± 0.26 | 0.04 | 0.70 | Small |
| Peak Grab Force (N) | 0.86 ± 0.23 | 0.92 ± 0.22 | 0.06 | 0.46 | Small |
| Peak Horizontal Force (N) | 1.24 ± 0.20 | 1.25 ± 0.16 | 0.01 | 0.82 | Small |
| Peak Vertical Force (N) | 1.28 ± 0.19 | 1.33 ± 0.20 | 0.05 | 0.43 | Small |
| Peak Power per Kilogram (w) | 56.20 ± 10.22 | 57.04 ± 11.17 | 0.84 | 0.81 | Small |

*Significant for $p < 0.05$

**Table 7 Underwater parameter comparisons for freestyle and butterfly**

| Parameter | Freestyle | Butterfly | Difference in Mean | P value | Effect Size |
|---|---|---|---|---|---|
| Time of Full Submersion (s) | 1.34 ± 0.05 | 1.35 ± 0.06 | 0.01 | 0.79 | Small |
| Time After Entry of First Kick (s) | 0.43 ± 0.23 | 0.46 ± 0.21 | 0.03 | 0.70 | Small |
| Time of First Kick (s) | 2.04 ± 0.26 | 2.06 ± 0.17 | 0.02 | 0.81 | Small |
| Horizontal Distance of Max depth (m) | 5.86 ± 0.95 | 6.68 ± 0.77 | 0.82 | 0.00* | Large |
| Max Depth of Head (m) | -0.91 ± 0.21 | -1.12 ± 0.22 | 0.21 | 0.01* | Large |
| Time at Max Depth (s) | 1.87 ± 0.39 | 2.16 ± 0.40 | 0.29 | 0.04* | Large |
| Time Underwater in Accent (s) | 2.59 ± 0.67 | 3.40 ± 0.53 | 0.81 | 0.00* | Large |
| Time Underwater in Descent (s) | 0.83 ± 0.39 | 1.12 ± 0.39 | 0.29 | 0.03* | Medium |
| Total Time Underwater (s) | 3.42 ± 0.92 | 4.52 ± 0.58 | 1.10 | 0.00* | Large |
| Underwater Velocity ($m \cdot s^{-1}$) | 2.41 ± 0.22 | 2.29 ± 0.13 | 0.12 | 0.02* | Medium |
| Breakout Distance (m) | 10.95 ± 1.84 | 13.19 ± 1.31 | 2.24 | 0.00* | Large |
| Time of Surfacing(s) | 4.46 ± 0.92 | 5.56 ± 0.61 | 1.10 | 0.00* | Large |
| Time to 5 m (s) | 1.56 ± 0.12 | 1.56 ± 0.11 | - | 0.98 | Small |
| Avg. Velocity 0-5 m ($m \cdot s^{-1}$) | 3.23 ± 0.25 | 3.23 ± 0.23 | - | 0.99 | Small |
| Time to 7.5 m (s) | 2.60 ± 0.26 | 2.53 ± 0.22 | 0.07 | 0.41 | Small |
| Avg. Velocity 5-7.5 m ($m \cdot s^{-1}$) | 2.45 ± 0.33 | 2.59 ± 0.31 | 0.14 | 0.17 | Medium |
| Time to 10 m (s) | 3.90 ± 0.36 | 3.79 ± 0.31 | 0.11 | 0.29 | Small |
| Avg. Velocity 7.5 -10 m ($m \cdot s^{-1}$) | 1.94 ± 0.18 | 2.01 ± 0.15 | 0.07 | 0.16 | Medium |
| Time to 15 m (s) | 6.55 ± 0.54 | 6.50 ± 0.51 | 0.05 | 0.74 | Small |
| Avg. Velocity 10-15 m ($m \cdot s^{-1}$) | 1.89 ± 0.14 | 1.85 ± 0.14 | 0.04 | 0.40 | Small |

*Significant for $p < 0.05$

### 4.5 Discussion

The data in this study supersedes previous studies of start techniques that are no longer used nor relevant to current competition techniques. In fact, swimmers can now gain an added advantage from using the additional kick plate on the new Omega OSB11 blocks. Honda et al. (2010) found that swimmers were able to produce more horizontal velocity off the blocks using the kick-start technique, which resulted in faster split times to 7.5 m.

The mean percentage time and absolute time contributions for each sub-phase of the swimming start in this study were in line with several previous swimming start studies using a variety of older start techniques. The on-block and flight phase contributions were the same as Blanksby et al. (2002) and Mason et al. (1997). Previous studies have not determined the exact time contribution of the underwater phase to overall start performance. Hence, in this study the time from head entry to 15 m was divided into two sections; the underwater and free-swimming phases. The swimmers spent the longest time in the underwater phase compared to the other sections of the start, which highlights its importance to overall start performance. Similar conclusions can be drawn when comparing the percentage contributions of each phase between genders. There were little differences between the on-block and flight phases. The main variances between male and female occurs during the underwater and free-swimming phases. Females had slower overall start performances, spent slightly less time underwater and more time free-swimming. From the results in this study there is evidence that the percentage time contributions are the same regardless of start technique and similar for gender. Therefore, the improvements in performance that come from the kick-start technique are due to the increase in magnitude of contribution of each sub-phase to overall start performance.

There were multiple differences between male and females which resulted in differences in performance. Male swimmers were faster, produced larger velocities and forces when compared to females. This is the same as an earlier study on elite swimmers by Miller et al. (1984). Furthermore, there were significant differences and large effects in take-off horizontal velocity (0.52 $m \cdot s^{-1}$, $p < 0.001$, Large), average acceleration (1.13 $m \cdot s^{-1}$, $p < 0.001$, Large) and entry velocity (0.35 $m \cdot s^{-1}$, $p < 0.001$, Large), which is the result of males being able to generate larger amounts of force. Hence, the higher take-off horizontal velocity displayed by the males was a result of the significant differences in peak horizontal force (0.22 BW, $p < 0.001$, Large).

For the underwater parameters there were also significant differences between genders. The differences occurred for maximum depth of head (0.20 m, $p > 0.001$, large) and breakout distance (1.33 m, $p = 0.02$, small). Males also had significantly higher underwater velocity split times and average velocity for all distance intervals. This was most likely due to the higher velocity the males are able to generate during the previous two phases of the start. Lyttle and Benjanuvatra (2005) stated that the phases preceding the swimmer's entry into the water (on block phase and flight phase) would directly affect the velocity the swimmer is able to achieve during the underwater phase of the start which is similar to the findings of this study. As both genders stayed underwater for approximately the same time the males were able to travel further due to higher underwater velocity than the females which resulted in better overall start performances. This finding supported those of Miller et al. (1984) who attributed the longer breakout distances in males to their greater height. However, height was not measured in this study so this point cannot be validated using the data from the present study.

Differences also existed between strokes for the underwater phase of the start but not for above - water parameters. This was different from the findings of Strojnik et al. (1998) who reported only small non-significant differences between each stroke during the swimming start. When compared to previous research, the results from this study displayed some significantly different values, particularly with the underwater parameters. Whitten (1997), from the analysis of grab starts also found that butterfly swimmers dive deeper that freestyle swimmers. A possible explanation for this may be that butterfly swimmers have a greater proficiency for the kick used in the underwater phase of the start, as its mechanics are similar to the kick used in the free swimming butterfly stroke. This would result in butterfly swimmers being able to achieve higher underwater velocities. Even though butterfly swimmers spent longer and travelled faster underwater there were no significant differences in overall start performances or split times. This would suggest that freestyle swimmers commence free swimming earlier and are able to compensate for a slower underwater velocity with higher free-swimming velocity.

## 4.6 Conclusions

This study was the first to use an instrumented start block and elite swimmers to characterise the main differences between male and female swimmers as well as examining differences between freestyle and butterfly starting technique. The importance of the underwater phase was clearly highlighted as swimmers spent the longest time in this phase and had the largest contribution to start performance. Practically, coaches and swimmers should place emphasis on improving the underwater phase. The results also show that there are clear variances in start performance between male and female athletes due to males being able to generate greater force and velocity in the early phases of the start which translate into faster overall start performances. There are also differences present for underwater parameters when comparing butterfly and freestyle, however these differences do not result in differences in time to 15 m.

# Chapter 5: Key Parameters of the Swimming Start and their Relationship to Start Performance

## Chapter 5.0 Key Parameters of the Swimming Start and Their Relationship to Start Performance

*From;* **Tor, E.,** Pease, D., Ball, K. (2014) (In Press). Key parameters of the swimming start and their relationship to start performance. *Journal of Sport Sciences. 33*(13), 1313.


### 5.1 Abstract

The swimming start is typically broken into three sub-phases; on-block, flight and underwater phases. While overall start performance is highly important to elite swimming, the contribution of each phase and important technical components within each phase, particularly with the new kick-start technique, has not been established. The aim of this study was to identify technical factors associated with overall start performance, with a particular focus on the underwater phase. A number of parameters were calculated from 52 starts performed by elite freestyle and butterfly swimmers. These parameters were split into above-water and underwater groupings, before factor analysis was used to reduce parameter numbers for multiple regression. For the above-water phases, 81% of variance in start performance was accounted for by take-off horizontal velocity. For the underwater water phase, 96% of variance was accounted for with time underwater in descent, time underwater in ascent and time to 10 m. Therefore, developing greater take-off horizontal velocity and focussing on the underwater phase by finding the ideal trajectory would lead to improved start performance.


### 5.2 Introduction

The swimming start is typically defined as the time from the starting signal to when the centre of the swimmer's head reaches 15 m (Cossor & Mason, 2001). During analysis, the swimming start is typically broken into three sub-phases. These phases are the on-block, flight and underwater phases (Cossor & Mason, 2001). The on-block phase is described as the time from the starting signal to when the swimmers' toe leaves the block while the flight phase is the time from when the swimmers' toe leaves the block to when the swimmers' head enters the water. The last and longest phase of the start is the underwater phase and is the time from when the swimmers' head enters the water to when the swimmer resurfaces to begin free swimming.

The swimming start has been consistently shown to be linked to overall performance during competition, particularly in shorter events (Cossor & Mason, 2001; Tor, Pease, Ball et al., 2014). Depending on the race distance the start can contribute between 0.8 to 26.1% of total race time (Cossor & Mason, 2001; Lyttle & Benjanuvatra, 2005). The start is also especially important because the maximum horizontal velocity at the start reaches approximately 4 $m{\cdot}s^{-1}$, which is more than twice the velocity of free swimming (Kiuchi, Nakashima, Cheng, & Hubbard, 2010). Honda et al. (2010) identified that an increase in horizontal velocity when the swimmer leaves the block improved time to 7.5 m. Therefore, to achieve better start performances swimmers must maximise the horizontal velocity generated during the on-block phase upon entry into the water and decrease the amount of deceleration during the underwater phase (Naemi & Sanders, 2008; Vantorre, Seifert, Fernandes, Vilas-Boas, & Chollet, 2010).

Scientists and coaches have reported a number of different start techniques that they believe would lead to the optimal start (Blanksby et al., 2002). However, in 2010 there was an introduction of a new start block (Omega OSB11) to all international competition. As a result of this introduction a modified starting technique called the "kick start" has been developed and utilised by most elite swimmers during current competition. Multiple research studies have already found that swimmers can gain an added advantage using this new technique (Biel et al., 2010; Honda et al., 2010; Nomura et al., 2010; Takeda et al., 2013). In a study using elite swimmers, Honda et al. (2010) reported this advantage to be 0.04 s to 7.5 m. This is mainly due to an increase in horizontal velocity (0.07 $m \cdot s^{-1}$) with the added contribution of the increased horizontal force (0.03 BW) that is able to be produced by the rear leg (Honda et al., 2010). These previous studies have focused on the initial above-water phases of the start, with research lacking once the swimmer enters the water following the kick-start. Hence, additional research must be conducted which aims to investigate the specific characteristics of the underwater phase based on the new modified track start (kick start) technique.

While all three sections of the start play a vital role in overall start performance, the underwater phase has been shown to be the most important (Elipot et al., 2009; Naemi et al., 2010; Thow et al., 2012; Tor, Pease, et al., 2014). This is because the underwater phase is the longest phase of the start and is when the swimmer is travelling at their fastest through the water (Elipot et al., 2009). Furthermore, the underwater phase can make up 94% of variance in overall start performance time (Guimaraes & Hay, 1985). The average velocity during this phase is highly dependent on horizontal velocity at entry and drag forces acting on the subject during the glide phase. Thow et al. (2012), Naemi et al. (2010) and Elipot et al. (2009) have previously investigated the underwater phase, however very little research has been conducted on the specific parameters (ideal trajectory, time spent underwater and depth) that comprise this phase.

Many parameters can determine overall starting performance including; velocity, the force the swimmer produces when leaving the block, angle of entry, velocity at entry, time spent underwater and underwater velocity (Cossor & Mason, 2001). The main purpose of this study was to determine which parameters would affect overall start performance (time to 15 m) the most, using the kick-start technique. To achieve this, a large number of retrospective dive starts collected on members of the Australian National Swimming team were analysed further and collated for additional data analysis. It was hypothesised that the underwater phase would make up a large amount of variance to start performance, in line with previous research (Guimaraes & Hay, 1985). Therefore, an added focus was placed on the parameters that occur during this phase.

### 5.3 Methods

Retrospective data were used in this study to determine the characteristics of elite swimmers during the swimming start. The Australian Institute of Sport (AIS) Performance Research Centre Ethics Committee provided ethical approval for this study. The data were selected from a database of all start trials tested using a customised force analysis system called the Wetplate Analysis System which was developed by the Australian Institute of Sport – Aquatic Testing, Training and Research Unit (ATTRU). The same analysis system has been used in a number of previous research papers (Honda, Sinclair, Mason et al., 2010, 2012; McCabe, Mason, & Fowlie, 2012; Tor, Pease, & Ball, 2014) and the reliability of parameters measured by this system have also been established previously (Tor, Pease, & Ball, 2015). The data were first filtered down to include only trials from 2010 onward, as prior to this there was no incline kick plate on the starting block and swimmers were tested in (the now banned) full body swimsuits. Further, to be included in the study the subjects in the trials must have made at least one senior Australian National Swimming team and specialise in either freestyle or butterfly. These strokes were chosen because they utilise similar start techniques (Tor, Pease, et al., 2014). Once the data were filtered there were a total of 52 trials (29 male (82.74 ± 9.03 kg, 23 ± 4 y), 23 female (68.23 ± 5.61 kg, 22 ± 3 y)) included in the study. Of these trials, 39 swimmers were Olympians (30 Olympic Medallists) and 14 were World Championship representatives. There were also 39 freestylers and 13 butterfliers included.

The Wetplate Analysis System measures a number of kinematic and kinetic parameters. A detailed list of these parameters can be found in Appendix 1. The proprietary system was developed by the AIS ATTRU and utilises an instrumented starting block with the same dimensions as the Omega OSB11 starting block used currently at all major international swimming competitions. The instrumented start block consisted of a tri-axial Kistler force platform (Z20314, Winterthur, Switzerland) angled at ten degrees, two Kistler tri-axial transducers (9601A) to measure grab force at the front of the block and an adjustable inclined kick plate with four tri-axial transducers (9251A). All force data were collected at 500 Hz and filtered using a 10 Hz low pass Butterworth filter.

The Wetplate system also incorporated four calibrated high-speed gigabit Ethernet (GigE) cameras (Pulnix, TMC-6740GE), collecting at 100 frames per second and positioned perpendicular to the action of the swimmer and the swimming pool (See Chapter 3, Figure 6). These cameras were calibrated using a series of poles of known lengths positioned at specifically known positions throughout the length of the area that the swimmers travelled during each trial. One camera was positioned 1.5 m above the water and 2 m perpendicular to the direction of travel to capture the start and entry (swimmer's head) into the water, while the other three cameras were positioned underwater at 1.6 m, 5.6 m and 12.8 m out from the start wall at 1.7 m below the surface of the water respectively to capture the subject swimming from entry to 15 m. The start signal was integrated into the analysis system and acted as a trigger to initiate data collection from all force plates and cameras. The intermediate splits for each trial were collected using a separate parallel timing system called "Swimtrak" that was also custom designed by the AIS. Swimtrak comprises eight analogue video cameras that are synchronised by time and sampling at 50 Hz (Samsung, SCC-C4301P) located perpendicular to the plane of motion at 0 m, 2.5m, 5 m, 7.5 m, 10 m, 15 m, 20 m and 25 m approximately 5 m above the surface of the pool. The time intervals were recorded as the centre of the swimmer's head passes the respective distances. Selected parameters were not measured at the time of testing and needed to be digitized separately by identifying the location of the apex of the swimmers' head at a number of pre-determined points during the swimming start. These parameters were average underwater velocity (head entry distance - breakout distance/time underwater water), time of full submersion, time after entry of first kick, time of first kick, total underwater time, time underwater in descent and time underwater in ascent.

### 5.3.1 Statistical Analysis

Descriptive statistics were calculated firstly for each parameter using SPSS (version 19.0, SPSS, Chicago, IL). Due to the large number of parameters measured, factor analysis was used to reduce the parameters to be included in multiple regression analysis. Parameters were then split into above-water parameters (parameters measured prior to the swimmer's entry into the water) and underwater parameters (parameters which were measured after the swimmer entered the water). A separate factor analysis was used for each parameter grouping. The analysis was separated to provide more detail of how each parameter affected overall start performance and to provide greater emphasis on the underwater phase as the swimmer spends the longest time during this section.

The number of factors was chosen using a cut off Eigen value of one, a principal component's extraction with a varimax rotation and a Scree plot. Kaiser-Meyer-Olkin (KMO) and Bartlett's test were used to ensure enough data were collected and to test for sphericity. A parameter was then allocated to each of the chosen factors based on loading scores. Similar analyses have been performed for other biomechanical analyses previously (Ball, 2008; Ball, Best, & Wrigley, 2003; Vantorre, Seifert, Fernandes et al., 2010). Genders were first separated for analysis, however similar trends existed within each group. Consequently, to increase subject numbers and statistical power, both genders and strokes were combined in the final analysis.

Once the main parameters were chosen from the factor analysis, a best subsets analysis was conducted using Minitab (Version 16). This determined the ‘best’ regression equation to predict start performance based on Mallow’s Cp (total square error) and best multiple $R^2$ assessment (Daniel & Wood, 1980). A regression was calculated for each combination of independent variables using time to 15 m as the dependent variable. The parameters chosen for the regression equation for each set of parameters (above-water and underwater) was based on the largest $R^2$ value and smallest Cp (error) value (Tabachnick & Fidell, 1996)

Following the best subsets analysis a full regression analysis was completed in SPSS and used to investigate the extent of the relationship between the main parameters and overall start performance (time to 15 m). While best subsets analysis gives the best regression for a given set of data and outputs overall $R^2$ and error values, it does not output information such as change in $R^2$ for individual parameters in the regression (Ball, Best, & Wrigley, 2001; Burkett, Mellifont, & Mason, 2010). Therefore, further multiple regression analysis on top of the best subsets analysis was needed. An additional multiple regression was also conducted on the underwater parameters with the split time and average velocity parameters removed to provide a more specific analysis of how these parameters affected the underwater phase.

To assess for univariate outliers z-scores were examined within each parameter. A score was deemed to be an outlier if it had a z-score greater than 3.29 (Tabachnick & Fidell, 1996). There was only one outlier present after univariate analysis (z-scores >3.29, $p = 0.001$). However, once bivariate outliers were assessed using subjective visual inspection of scatterplots with no outliers present, this parameter was included in further analysis.

Following the best subsets analysis and prior to full regression analysis, the data were screened for multivariate outliers. This was done by using Mahalonobis Distance with a cut off level of $p < 0.001$ (Tabachnick & Fidell, 1996). After the completion of full regression analysis DFIT and residuals were examined to further determine if multivariate outliers were present in the data. Once all of these diagnostic tests were completed it was established that there were no outliers present in the data for each parameter and all cases were included in the analysis.

## 5.4 Results

The Scree plot and factor analysis revealed three main factors for above-water parameters and four main factors for the underwater parameters. Take-off horizontal velocity, take-off vertical velocity and time on-block were chosen as the parameters to represent each main factor score for the above-water parameters. Time to 10 m, time underwater in descent, time underwater in ascent and time at first kick were chosen as the parameters to represent each main factor score for the underwater parameters.

Best subsets analysis produced a number of equations with different combinations of parameters (predictors) based on the factor analysis scores. The best equation is highlighted and displayed in Table 8 (based on overall $R^2$ and Cp values). A number of additional predictor combinations were completed but were not reported as the overall $R^2$ and Cp values were not as high. For the above-water parameters the equation with two predictors; take-off horizontal velocity and time on-block was selected as the best equation to predict time to 15 m. For the underwater parameters the best equation to predict time to 15 m contained three predictors; time underwater in descent, time underwater is ascent and time to 10 m.

**Table 8 Minitab Best Subsets output**

| **On Block Parameters** | | | | | | |
|---|---|---|---|---|---|---|
| **Vars (p)** | ***$R^2$*** | **Cp** | **Take-off Horizontal Velocity** | **Take-off Vertical Velocity** | **Time on Block** | |
| 1 | 80.0 | 2.4 | x | | | |
| 1 | 25.4 | 140.3 | | | x | |
| **2** | **81.0** | **2.1** | **x** | | **x** | |
| 2 | 80.4 | 3.4 | x | x | | |
| 3 | 81.0 | 4.0 | x | x | x | |
| **Underwater Parameters** | | | | | | |
| **Vars (p)** | ***$R^2$*** | **Cp** | **Time UW in Descent** | **Time UW in Ascent** | **Time to 10 m** | **Time of First Kick** |
| 1 | 94.4 | 20.5 | | | x | |
| 1 | 3.3 | 1125.3 | x | | | |
| 2 | 95.8 | 4.6 | x | | x | |
| 2 | 95.4 | 9.6 | | x | x | |
| **3** | **96.1** | **3.0** | **x** | **x** | **x** | |
| 3 | 95.8 | 6.6 | x | | x | x |
| 4 | 96.1 | 5.0 | x | | x | x |

*Note:* Best equation highlighted. Vars = predictor variables

For the above- water parameters the regression equation produced using the predictors identified from the best subsets analysis was able to account for 81% ($R^2 = 0.81$, $p < 0.001$) of the variance in overall start performance (time to 15 m) (Table 9). For the underwater parameters the overall regression equation was able to explain 96% of variance in start performance ($R^2 = 0.96$, $p < 0.001$). The additional multiple regression of the underwater parameters revealed that 85% of variance during the underwater phase can be accounted for by time of maximum depth, horizontal distance of maximum depth and time of first kick ($R^2 = 0.85$, $p = 0.04$).

**Table 9 Results from multiple regression analysis**

**On Block Parameters**

| Parameter | B | $R$ | $p$ | Full Model | |
|---|---|---|---|---|---|
| Constant | 12.31 | | 0.00* | $R$ | 0.90 |
| Take-off Horizontal Velocity | -1.42 | -0.90 | 0.00* | $R^2$ | 0.81 |
| Time on Block | 1.07 | 0.50 | 0.13 | $p$ | 0.00 |

**Full Equation**

Time to 15 m = 12.21 - 1.42(Take-off Horizontal Vel.)

**Underwater Parameters**

| Parameter | B | $R$ | $p$ | Full Model | |
|---|---|---|---|---|---|
| Constant | 0.51 | | 0.01* | $R$ | 0.98 |
| Time to 10 m | 1.50 | 0.05 | 0.00* | $R^2$ | 0.96 |
| Time UW in Ascent | 0.05 | 0.02 | 0.06* | $p$ | 0.00 |
| Time UW in Descent | 0.12 | 0.04 | 0.01* | | |

**Full Equation**

Time to 15 m = 0.51 + 1.50(Time to 10 m) + 0.05(Time UW in Ascent) + 0.12(Time UW in Descent)

*Significant for $p < 0.05$

### 5.5 Discussion

This study used elite swimmers to identify the key parameters that affect the overall start performance. While this study investigated all phases of the start, particular focus was made on the underwater phase of the swimming start as this phase has previously been shown to be the most decisive in determining overall start performance (Cossor & Mason, 2001; Thow et al., 2012).

Analysis of the above-water parameters found that take-off horizontal velocity and time on-block were the key parameters. These findings were similar to previous studies which used correlation analysis and found that there was a strong relationship between these parameters and time to 15 m (Breed & McElroy, 2000; Galbraith, Scurr, Hencken, Wood, & Graham-Smith, 2008). However, when all parameters where included in the multiple regression analysis only take-off horizontal velocity was shown to be significant and included in the equation to predict start performance (time to 15 m). It was found that this parameter could account for 81% of the variance in start performance. An increase in take-off horizontal velocity would typically result in the swimmer entering the water at a flatter angle. Hence, the effect of increasing this parameter can be negated if the swimmer does not maintain velocity during the underwater phase, due to an increased amount of resistance acting on them. This further highlights the importance of identifying the ideal underwater trajectory to reduce the amount of deceleration that occurs during the underwater phase following entry into the water.

A reduction in time on-block would have an absolute reduction on time to 15 m (Garcia-Hermoso et al., 2013), however some studies have suggested that there is a trade-off between time on-block and horizontal velocity due to a decrease in impulse (Breed & McElroy, 2000; Vantorre et al., 2010e). Swimmers can actively reduce their on-block time by anticipating the start and increasing lower body strength and power, although this could compromise impulse (Garcia-Hermoso, Escalante, Arellano et al., 2013). Vilas-Boas, Cruz, Conceicao, and Carcalho (2000) and Gibson and Holt (1976) have shown (using the grab start technique) that higher impulses contribute greatly to higher horizontal velocities at take-off and water entry. Consequently, a reduced time on-block may have negative effects on force generating parameters due to a smaller impulse. On the other hand, Honda et al. (2010) stated that with the use of the kick plate swimmers can decrease time on-block without compromising horizontal velocity due to the raised back foot which allows force application in a more horizontal direction. Honda et al. (2010) did not use time to 15 m as the performance measure, instead they used time to 7.5 m which may account for the differences to the current study.

Thus, swimmers need to focus on increasing their take-off horizontal velocity without decreasing their time on the block. Possible strategies to achieving this would be to increase muscular strength and power of the lower body and to also ensure that momentum is summed by ensuring the swimmer is sequencing their joints correctly during the dive action (West, Owen, Cunningham, Cook, & Kilduff, 2001).

In addition, multiple studies have also stated the importance of maximising the flight phase of the swimming start as this phase has less resistance which would subsequently allow swimmers to maximise their velocity during the underwater phase (Bloom et al., 1978; Breed & McElroy, 2000; Pearson et al., 1998; Vantorre et al., 2010e). However in this study, time in the air (flight time) and entry distance were not identified as influential parameters to start performance. This variation in results from previous research can be explained by the obvious differences in start technique and the increased horizontal velocity generated from the new kick-start technique (Honda et al., 2010). A greater horizontal velocity would result in a flatter aerial trajectory and less time in the air before the swimmer enters the water (Costill, Maglishco, & Richardson, 1992), negating its importance to overall start performance.

The key parameters identified during the underwater phase of the swimming start were time to 10 m, time underwater in descent and time underwater in ascent. These parameters have been shown to account for 96% of the variance in start time. This figure is similar to Guimaraes and Hay (1985) who found that the underwater phase accounted for 94% of overall start performance. Given this, these results supported the findings from previous research on the importance of the underwater phase to better start performance (Elipot et al., 2009; Naemi & Sanders, 2008; Vantorre et al., 2010e). This is also supported in a similar study by Burkett et al. (2010) who used 20 male Olympic and Paralympic swimmers and found that underwater velocity was one of the parameters that significantly affected start performance. Conversely, this study differed from the present study, as they did not use the Omega OSB11 block during testing. Furthermore, within the underwater phase, time to 10 m was clearly the strongest predictor of start performance based on statistical analysis. This would seem logical as a faster 10 m time would likely lead to a fast time to 15 m. However, Vantorre (2010e) and Lyttle and Benjanuvatra (2005) found a number of above-water parameters in the first two phases of the start that had strong correlations to underwater velocity. Therefore, even though time to 10 m was a strong predictor of start performance there are other elements of the start that would contribute to this parameter such as take-off horizontal velocity, underwater velocity and free-swimming velocity. All of these parameters were highly related and would affect the trajectory that the swimmer is travelling during the underwater phase which would have implications on the amounts of drag acting on the swimmer (Naemi, Easson, & Sanders, 2010; Tor, Pease, & Ball, 2015).

Time underwater in descent and time underwater in ascent were also identified as important parameters during the underwater phase. Time underwater in descent and time underwater in ascent combined together equate to the total time underwater and essentially describes the trajectory used by the swimmer during the underwater phase. As these parameters are difficult for the swimmer to control, extra analysis of the underwater phase identified that time of maximum depth, horizontal distance of maximum depth and time of first kick would also significantly affect start performance. Additionally, changing the swimmers' underwater trajectory is dependent on a number of different factors including; hydrodynamics (anthropometric characteristics and resistance) and underwater kicking ability (Guimaraes & Hay, 1985; Houel, Elipot, Andre et al., 2012; Pereira, Ruschel, & Araujo, 2006). Previous research would suggest that the correct combination between time underwater in descent and ascent before resurfacing is individual, as every swimmer's anthropometric characteristics and underwater kicking ability is different (Lyttle, Blanksby, Elliott, & Lloyd, 1999). Consequently, more research is needed to precisely identify the correct individual combination of these parameters that would allow swimmers to effectively maintain the velocity generated during the first two phases of the start as they enter the water.

### 5.6 Conclusion

This study used elite subjects to identify the key parameters that contribute to overall start performance using the kick-start technique. Even through many parameters contribute to swimming start performance, there are elements of the start that have been proven to affect overall start performance more than others, such as take-off horizontal velocity, time to 10 m, time underwater in descent and time underwater in ascent. Using the information from this study, derived from statistical analysis, swimmers should focus on the underwater phase of the start, specifically maximum depth, horizontal distance of maximum depth and timing of first kick so that they are able to reach the 10 m as fast as possible. These parameters have all been identified as priority areas that can be trained explicitly to improve start performance. Therefore, more research into the interaction between underwater kick ability, hydrodynamic drag and anthropometric characteristics would give coaches a more individualised approach for improving start technique by adopting the ideal underwater trajectory. Travelling at the ideal underwater trajectory would allow the resistance acting on the swimmer to be reduced and consequently, the swimmer would be able to maintain a higher velocity following entry into the water for longer, leading to better start performances.

# Chapter 6: Do Swimmers Always Perform Better Using Their Preferred Technique?

# Chapter 6.0 Do Swimmers Always Perform Better Using Their Preferred Technique?

*From:* **Tor, E.,** Pease, D., Ball, K. (2015) (In Review). Do swimmers always perform fastest using their preferred technique? International Society of Sport Biomechanics Conference 2015. Portiers, France.


## 6.1 Abstract

This study compared four underwater trajectories in order to determine if swimmers would always perform fastest using their preferred technique. Fourteen elite swimmers were asked to dive at three depths as well as their preferred dive. These conditions were labelled as Dive 1, Dive 2, Dive 3 and Preferred. The Wetplate Analysis System was used to collect all data before descriptive statistics were determined. Inter-trial variability on a group basis revealed little difference in variance between each dive type. Further individual analyses found that seven of the fourteen swimmers performed faster using a non-preferred technique. In contrast to other studies which have found that swimmers would favour their preferred start technique there is evidence in this study to suggest that elite swimmers are able to readily change their underwater trajectory.


## 6.2 Introduction

In sport there have been multiple studies that have compared different techniques in order to determine if there is an “ideal movement pattern” which athletes must adopt in order to achieve superior performance. Specifically investigating the swimming start, there have also been a number of studies that have manipulated the swimmers’ technique with the aim of improving performance (Honda et al., 2012; Kirner et al., 1989; Slawson et al., 2011). Hay (1986) stated that most studies comparing different start techniques are flawed as swimmers would always perform better using their preferred start technique. Indeed, there are a number of studies that have shown swimmers would perform better with their preferred dive as this technique is more stable and reproducible (Hay, 1986; Jorgic et al., 2010; Vantorre et al., 2010).

There is also evidence in these studies that elite swimmers are able to readily change their technique, which suggests that these types of comparative studies are not flawed when using elite swimmers. Vantorre et al. (2010) compared elite swimmers preferential start technique with an un-preferential technique. They found that even through there were differences in kinematics prior to entry into the water, there were no differences in overall performance; stating that high-level swimmers are able to compensate lower block efficiency with effective underwater phases. Similarly, White et al. (2011) used experienced and less experienced swimmers to compare shallow and deep underwater trajectories and found that the more experienced swimmers were able to readily alter their technique.

The current study utilised a comparative design with elite swimmers only, aiming to determine if swimmers performed better using their preferred underwater trajectory. It was hypothesised that swimmers are likely to perform better using their preferred technique. Nevertheless, this study’s protocol would encourage swimmers to try a new technique, which may prove to be faster.

## 6.3 Methods

Fourteen swimmers (11 male, 3 female, 19 ± 1 y) were recruited from the Australian Institute of Sport (AIS) Swimming Program and other state institute programs around Australia. All swimmers qualified for the National Championships in the 100 m freestyle (53.10 s for male, 59.00 s for female) and had at least 5 years of competitive swimming experience at the national level with an average FINA point score of 787 ± 19.

Swimmers were asked to perform a series of dives at three depths. The depths were categorised as Dive 1, Dive 2, Dive 3 and the swimmers' preferred dive. Dive 1 is typically characterised by swimmers resurfacing as fast as possible with minimal underwater kick. This is the dive used mostly by swimmers who are weak at underwater kick as they spent the shortest amount of time underwater. During Dive 1 the swimmers were asked to resurface and commence free swimming almost immediately after entry. Dive 2 can be described as a gradual descent followed by a gradual ascent. For Dive 2 the swimmers were asked to dive deeper and aim to resurface around the 10 m mark. Finally, Dive 3 is most commonly used by swimmers who are highly proficient in underwater kick, as the swimmer stays underwater for the longest amount of time during this dive. In Dive 3 the swimmers were asked to dive down deep and resurface to commence free swimming at the 15 m mark.

To assist the subjects in achieving the prescribed trajectories, brightly coloured markers were placed at 5 m, 7.5 m and 9 m on the bottom of the pool, to indicate the point at which the subjects needed to begin rising to the surface in order to achieve the Dive 1, Dive 2 and Dive 3 conditions respectively. The distances that the markers were placed at was determined from a previous study by Tor et al. (2014) which stated that the mean horizontal distance of maximum depth for elite swimmers is 6.06 m with a standard deviation (SD) of 0.97 m. Therefore, the markers were placed at -1 SD (5 m), +1.5 SD (7.5 m) and +3 SD (9 m) according to the results of that previous study. The swimmers performed 16 dives at maximum effort to 15 m (4 dives at each set condition and 4 dives at their preferred depth) with two minutes rest in between each dive. The 16 dives were completed over two testing sessions (one day rest in between each session); eight dives per session. Each swimmer performed two of each dive type during the session in a randomized order. Testing was divided into two testing sessions to ensure that each trial was performed maximally by the swimmer. Each dive trial was tested using the Wetplate Analysis System. The Wetplate Analysis System is a propriety system developed by the AIS Aquatic Testing, Training and Research Unit (ATTRU) and consists of an instrumented starting block with the same dimensions as the Omega OSB11 starting block (that used at all major international competitions) and a series of high-speed camera (Tor, Pease, & Ball, 2015). The Swimtrak time system was used simultaneously to measure split times.

Individual analysis was first conducted on the data using standard deviation as a measure of inter-trial variability. Each swimmer's fastest dive condition was identified and tabulated. Means and standard deviations were then calculated for each parameter using SPSS Statistical Package (version 19.0, SPSS, Chicago, IL).

## 6.4 Results

Performance time (time to 15 m) and descriptive statistics of selected parameters for each dive condition are shown in Table 10. The mean and standard deviation of each dive type for performance time was Dive 1 (mean ± standard deviation, 6.62 ± 0.40 s), Dive 2 (6.54 ± 0.37 s), Dive 3 (6.56 ± 0.42s) and Preferred (6.48 ± 0.39s).

Each swimmer's fastest dive condition was also identified on an individual basis. On seven occasions out of 14 the swimmer's preferred dive was not the fastest dive condition and on two occasions the fastest condition equalled the swimmer's preferred condition. Two swimmers each found that Dive 1 and Dive 3 were the fastest condition, while three swimmers found that Dive 2 was the fastest.

**Table 10 Mean and standard deviation of selected parameters for each dive condition**

| Parameter | Preferred | Dive 1 | Dive 2 | Dive 3 |
|---|---|---|---|---|
| **Maximum Depth (m)** | -0.98 ± 0.17 | -0.74 ± 0.14 | -0.92 ± 0.16 | -1.03 ± 0.18 |
| **Time at Max Depth (s)** | 1.78 ± 0.23 | 1.53 ± 0.18 | 1.75 ± 0.22 | 1.98 ± 0.46 |
| **Breakout Distance (m)** | 11.91 ± 1.52 | 8.11 ± 1.20 | 10.50 ± 1.41 | 12.43 ± 1.14 |
| **Breakout Time (s)** | 4.85 ± 0.69 | 2.94 ± 0.55 | 4.13 ± 0.68 | 5.22 ± 0.58 |
| **Depth of first kick (m)** | -0.98 ± 0.20 | -0.50 ± 0.24 | -0.89 ± 0.18 | -1.04 ± 0.17 |
| **Distance of first kick (m)** | 6.54 ± 0.68 | 6.16 ± 0.57 | 6.62 ± 0.68 | 6.65 ± 0.69 |
| **Time of First Kick (s)** | 2.04 ± 0.23 | 1.96 ± 0.19 | 2.08 ± 0.24 | 2.09 ± 0.24 |
| **Time to 15 m (s)** | 6.48 ± 0.39 | 6.62 ± 0.40 | 6.54 ± 0.37 | 6.56 ± 0.42 |

### 6.5 Discussion

Most dive start studies have reported that swimmers' performed their best starts using a technique which they had the most practice with (Pearson et al., 1998). When examining different starting techniques, Hay (1986) stated that most studies are flawed because swimmers all have their own preferred start that is practiced almost exclusively. Therefore, studies which suggest one type of starting technique is superior to another may usually be associated with the swimmer's preference rather than real biomechanical advantages (Lyttle & Benjanuvatra, 2005). Further, an athlete's perception of their ability (sport confidence) and comfort in performing a skill (preference) may also affect their physical performance (Mills & Gehlsen, 1996). This study aimed to determine if swimmers always perform better with their preferred technique.

In this study, multiple individual analyses were used to determine if swimmers performed fastest using their preferred technique. Using standard deviation as a measure of inter-trial variability, there is very little difference in performance between each dive type and the swimmer's preferred condition. Even though previous research stated that the swimmers' preferred start technique is also the most stable and reproducible (Vantorre et al., 2010), there is evidence to suggest that this type of study is not flawed and that skilled swimmers are able to adjust from their preferred starting technique with similar amounts of inter-trial variability present for all dive conditions.

There is also evidence in this study that the swimmers' preferred technique is not the fastest. Each individuals fastest dive type was determined and showed that half of the subjects performed faster using a non-preferred technique. Hence, even though the subjects were considered highly competitive, a number of swimmers still had not optimised their performance and could further improve their start technique by altering their underwater trajectory. This was different to previous studies that have suggested swimmers would always perform better using their preferred or most practiced technique.

In addition, this study found that all swimmers were able to modify the maximum depth of their starts. White, Cornett, Wright, Willmott, and Stager (2011) tested 12 competitive and 13 less experienced swimmers at two different depths (preferred and shallow) and have shown swimmers with more competitive experience have been able to change the depth of their starts in comparison with less experiences swimmers. Conversely, in a study comparing two different start techniques Vantorre et al. (2010) found that there were no significant differences between the two techniques, stating that skilled swimmers were able to compensate lower block efficiency with effective underwater phases and there were no significant differences. Given that there was difference in maximum depth between each dive condition and some swimmers performed better using a non-preferred technique, the results from the present study and White et al. (2010) suggest that elite swimmers are able to adapt to a non-preferred technique with little training.

### 6.6 Conclusion

This study compared four underwater trajectories using an instrumented starting block and kick-start technique. Using this study design in the future coaches would be able to determine if their swimmers have optimised their underwater trajectory to improve start performance. Contrary to other studies this study found that elite swimmer's preferred movement pattern may not be their optimal technique. Elite swimmers, like the ones used in this study are able to change their technique with little training. Consequently, the findings of this study suggest that this type of design, when used with elite subjects is not flawed and can be applied in the future.

# Chapter 7: Comparing Three Underwater Trajectories

**Chapter 7.0 Comparing Three Underwater Trajectories**

*From:* **Tor, E.,** Pease, D., Ball, K. (2014) (In Press) Comparing three underwater trajectories of the swimming start. *Journal of Science and Medicine in Sport.* Accepted for Publication: 29th October 2014

## 7.1 Abstract

Once a swimmer enters the water they would not increase velocity, instead they would decelerate. One factor that would influence the velocity maintained during the underwater phase is the trajectory the swimmer adopts. This study aimed to identify how different underwater trajectories that affect start time in elite swimmers. Fourteen swimmers performed three dives; a shallow dive with little underwater time (Dive 1), a flatter dive with intermediate time underwater (Dive 2) and a deep dive with lengthy underwater time (Dive 3). The proprietary 'Wetplate' analysis system was used to collect performance time (time to 15 m) and 36 other dive parameters. A mixed modelling approach found Dive 1 was significantly slower than Dive 2 and 3 (time to 15 m). This indicated that both a shallow or deep dive slowed overall performance, with shallower dives adversely affecting performance the most. On average using a flatter trajectory with a maximum depth of (-0.92 ± 0.16 m) similar to Dive 2 may prove to be beneficial to start performance. More research is needed to examine the interaction between drag and depth for individual swimmers to better underwater the mechanisms influencing these findings and to further explore the notion of an ideal underwater trajectory.

## 7.2 Introduction

Start time, which consists of the on-block, flight and underwater phases, has been strongly correlated to overall performance in competitive swimming (Cossor & Mason, 2001). The on-block phase is defined as the time between the starting signal and the time when the swimmer's feet leave the blocks. The flight phase is the interval between the swimmer's toe leaving the block and the swimmer's head making contact with the water while the underwater phase is defined as the interval between head contact with the water and the head re-surfacing to commence free swimming. Furthermore, total start time is calculated as the time from the starting signal to when the centre of the swimmer's head reaches the 15 m mark (Cossor & Mason, 2001).

The underwater phase is the longest phase of the start and has been shown on multiple occasions to be the most decisive in determining efficient overall start performance (Cossor & Mason, 2001; Naemi & Sanders, 2008; Thow et al., 2012). The underwater phase can be further sub-divided into the glide and underwater kicking phases. This phase is crucial to overall race performance because after the dive itself this is the next fastest section of the race and has been shown to account for 95% of variance in start time (Connaboy, Coleman, Moir, & Sanders, 2010; Tor, Pease, & Ball, 2014). Through correlational analysis of start performances at the Sydney 2000 Olympics, Cossor and Mason (2001) found that underwater distance was negatively correlated to performance. Therefore, as the swimmers remained longer underwater, time to 15 m is reduced, indicating a faster start time.

Once the swimmer enters the water, with a horizontal velocity of about 6 $m.s^{-1}$ they would not increase velocity, instead they would adopt a streamline position and kick until they slow to near their free-swimming pace (Tor, Pease, et al., 2014). Kirner et al.(1989) state that coaches should realise the swimmer who enters the water first is not necessarily the most effective starter. Consequently, to achieve faster starts, swimmers must learn to decrease deceleration as they enter the water and progress through the underwater phase before commencing free swimming (Naemi & Sanders, 2008).

There are a number of factors that would affect the swimmer after they enter the water that would determine how much velocity is maintained and in turn the overall outcome of the start. These include being as streamlined as possible, starting underwater undulatory swimming after about 6 m, and generating propulsive kick using only the feet and legs during the underwater water kick phase (Houel et al., 2012). The swimmer can also vary the depth at which they are travelling, although this would affect wave drag and has implications on the trajectory of the underwater phase (Naemi & Sanders, 2008; Sanders, 2002; Thow, Naemi, & Sanders, 2012).

The ideal underwater trajectory has not yet been determined for the kick-start technique using the new Omega OSB11 starting block. Given the already established importance of trajectory and depth for better start performances, the aim of this study is to compare three underwater trajectories used by swimmers to determine how they influence start performance. It is hypothesised that the ideal underwater trajectory would be an optimal depth to reduce the amount of drag acting on the swimmer, while still enabling the swimmer to travel in the desired horizontal direction.

### 7.3 Methods

This study was approved by the Australian Institute of Sport (AIS) Performance Research Ethics Committee. Fourteen swimmers (11 male, 3 female, 19 ± 1 y) were recruited from the AIS and other state institute swimming programs around Australia. All swimmers were considered highly competitive, with two Olympic representatives, two World Championship representatives and eight Australian National Open Finalists. All swimmers were able to qualify for the National Championships in the 100 m freestyle (53.10 s for male, 59.00 s for female) and had at least 5 years of competitive swimming experience at the national level. Only freestyle was chosen for this study because a previous study by Tor et al.(2014) found that there were differences during the underwater phase between freestyle and butterfly.

Prior to testing, each swimmer performed their usual pre-race warm-up and were given at least three practice trials per dive type to ensure that they were able to perform each condition adequately. Swimmers were asked to perform a series of dives at three depths (A visual representation can be found in Appendix II). The depths were categorised as Dive 1, Dive 2 and Dive 3. Dive 1 is typically characterised by swimmers resurfacing as fast as possible with minimal underwater kick. During Dive 1 the swimmers were asked to resurface and commence free swimming almost immediately after entry. Dive 2 was a gradual descent followed by a gradual ascent. For this dive, the swimmers were asked to dive deeper and aim to resurface around the 10 m mark. Finally, in Dive 3 the swimmers were asked to dive down deep and resurface to commence free swimming at the 15 m mark.

To assist the subjects in achieving the prescribed trajectories, brightly coloured weighted markers were placed at 5 m, 7.5 m and 9 m on the bottom of the pool, to indicate the point at which the subjects needed to begin rising to the surface in order to achieve Dive 1, Dive 2 and Dive 3 trajectories respectively. The distances that the markers were placed at was determined from a previous study by Tor et al.(2014) which found that the mean horizontal distance of maximum depth for elite swimmers is 6.06 m with a standard deviation (SD) of 0.97 m. Therefore, the markers were placed at -1 SD (5 m), +1.5 SD (7.5 m) and + 3 SD (9 m) according to the results of that previous study.

The swimmers performed 12 dives with maximum effort to 15 m (4 dives for each dive type) with two minutes rest in between each dive. The 12 dives were completed over two testing sessions (one day rest in between each session) to avoid any fatigue effects and to ensure that each trial was performed maximally by the swimmer; six dives per session. Each swimmer performed two of each dive type during the session in a randomized order.

Each dive trial was tested using the Wetplate Analysis System. The Wetplate Analysis System is a proprietary system developed by the AIS Aquatic Testing, Training and Research Unit (ATTRU) and consists of an instrumented starting block with the same dimensions as the Omega OSB11 starting block (that is used at all major international competitions) and a series of high-speed cameras (Mason, Mackintosh, & Pease, 2012). Performance time was measured using a second proprietary system, 'Swimtrak', which is made up of eight analogue video cameras (Samsung, SCC-C4301P) located perpendicular to the plane of motion at 0 m, 5 m, 7.5 m, 10 m, 15 m, 20 m and 25 m and positioned approximately 5 m above the surface of the pool.

Female and Male subjects were combined in all analyses to increase statistical power. Although differences in gender have been identified in a previous study by Tor et al.(2014), these differences were accounted for by adding gender as a covariate in the analysis. The data was coded to identify each dive type and gender. All of the dive conditions were pooled on a group basis for analysis ie. 56 trials for each dive condition. Prior to mixed modelling, each parameter was graphed for visual inspection to screen for outliers. As there were no outliers, all data was included in further analysis. Mixed modelling was used to make comparisons between each dive type. Start performance was defined as Time to 15 m. The fixed factors were the dive type and a new variable, which was created to allow for an interaction to be included for gender and dive type (gender x dive type), while the random effects were the subjects' given name. The new variable was added to each model because a limitation of SPSS Statistical Package is that pairwise comparisons for an interaction term are not generated unless a new variable is created. Consequently, the new variable allowed for pairwise comparisons to be made between each group combining gender and dive type separately. The same model was used for all analyses; however each parameter was included as a separated dependent variable. Pairwise comparisons with a Bonferonni correction were then used to make specific comparisons between each parameter. Significance was set at $p < 0.05$, although difference in mean and 95% confidence intervals were reported as well, to provide information about the extent of the differences between each group.

## 7.4 Results

The descriptive statistics for each dive type (Table 11) confirmed that each dive type was executed as instructed. These trajectories were chosen because they are the three most widely used trajectories used by elite swimmers. There was also a significant main effect ($F_{2,150} = 3.37$, $p = 0.04$) for maximum depth with an interaction for gender (Figure 8). The above-water parameters (prior to entry into the water) showed no significant differences for all dive types, with the majority of differences only seen in the underwater water parameters.

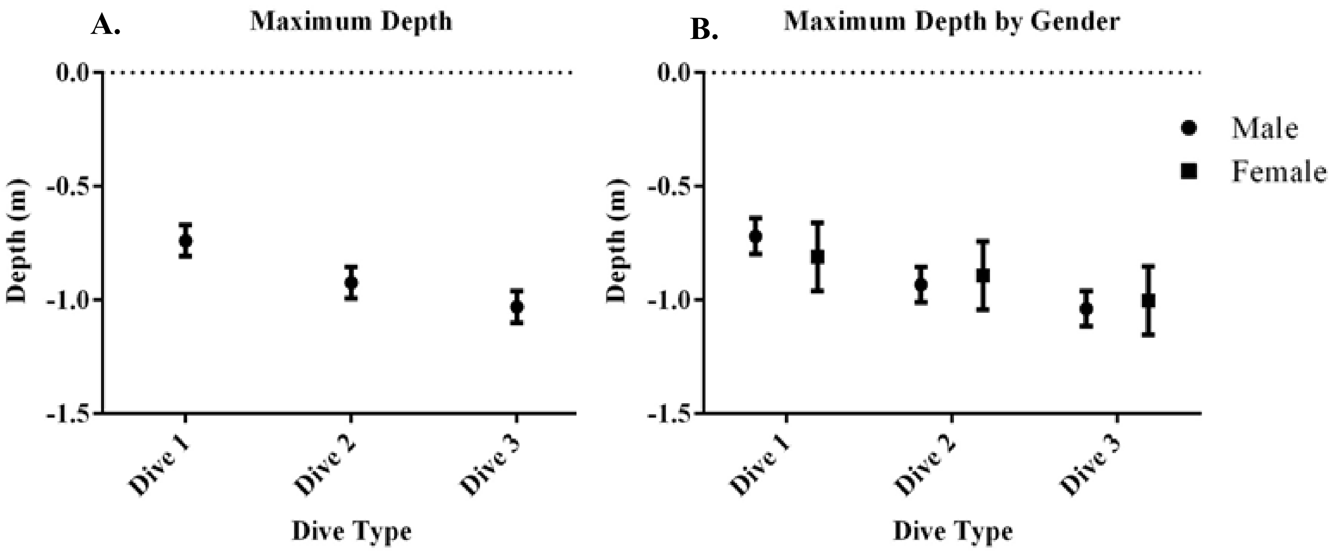



**Figure 8 A: Maximum depth for each dive condition on a group basis, B: Maximum depth for each dive condition split by gender. The bars indicate the 95% confidence intervals for each condition.**

For the underwater parameters, there was a significant main effect ($F_{2,150} = 3.37$, $p = 0.04$) for maximum depth with an interaction for gender (Figure 8). This was the only parameter to show a significant interaction for gender. Although, the plots of this parameter revealed a similar trend regardless of gender, this was most likely due to the smaller number of female subjects and would not affect the outcomes of the study. Total underwater water time also varied between dive conditions ($F_{2,150} = 65.19$, $p < 0.001$). Dive 3 spent the most time underwater (4.16 s), followed by Dive 2 (3.07 s) and Dive 1 (1.88) respectively. This was closely linked to the significant differences between each dive type also exhibited for breakout time ($F_{2,150} = 65.10$, $p < 0.001$) and breakout distance ($F_{2,150} = 47.40$, $p < 0.001$). Time of first kick also differed between dive types $F_{2,1502}= 23.23$, $p < 0.001$), specifically there were differences between Dive 1 and Dive 2 (-0.13 s, -0.18 to -0.07, $p < 0.001$) and Dive 1 and Dive 3 (-0.14 s, -0.19 to -0.08, $p = 0.003$).

**Table 11 Descriptive statistics for each dive condition and indication of significant differences from pairwise comparisons**

| Parameter | Dive 1 | Dive 2 | Dive 3 |
|---|---|---|---|
| Reaction Time (s) | 0.71± 0.04 | 0.72 ± 0.04 | 0.72 ± 0.04 |
| Time in the Air (s) | 0.34 ± 0.05 | 0.34 ± 0.05 | 0.35 ± 0.04 |
| Dive Angle (º) | -11.7 ± 3.9 | -11.6 ± 4.0 | -11.4 ± 3.9 |
| Entry Distance (m) | 2.94 ± 0.15 | 2.96 ± 0.16 | 2.96 ± 0.13 |
| CoG Entry Angle (º) | 46.8 ± 2.2 | 46.6 ± 2.1 | 46.8 ± 2.1 |
| Time Head Enters (s) | 1.06 ± 0.06 | 1.06 ± 0.06 | 1.06 ± 0.06 |
| Entry Velocity ($m.s^{-1}$) | 6.81 ± 0.14 | 6.80 ± 0.14 | 6.80 ± 0.13 |
| Peak Power per Kilogram (w/kg) | 60.46 ± 6.73 | 61.41 ± 6.62 | 60.91 ± 6.50 |
| Take-off Horizontal Velocity ($m \cdot s^{-1}$) | 4.65 ± 0.24 | 4.66 ± 0.23 | 4.65 ± 0.23 |
| Take-off Vertical Velocity ($m \cdot s^{-1}$) | -0.97 ± 0.36 | -0.97 ± 0.36 | -0.96 ± 0.35 |
| Distance at Max Depth (m)*^# | 5.03 ± 0.58 | 5.75 ± 0.69 | 6.32 ± 1.21 |
| Max Depth (m)*^# | -0.74 ± 0.14 | -0.92 ± 0.16 | -1.03 ± 0.18 |
| Time at Max Depth (s)*^# | 1.53 ± 0.18 | 1.75 ± 0.22 | 1.98 ± 0.46 |
| Total Underwater Time (s)*^# | 1.88 ± 0.55 | 3.07 ± 0.67 | 4.16 ± 0.57 |
| Time in UW Descent (s)*^# | 0.47 ± 0.18 | 0.69 ± 0.22 | 0.91 ± 0.45 |
| Time in UW Ascent (s)*^# | 1.41 ± 0.42 | 2.39 ± 0.54 | 3.24 ± 0.58 |
| Breakout Distance (m)*^# | 8.11 ± 1.20 | 10.50 ± 1.41 | 12.43 ± 1.14 |
| Breakout Time (s)*^# | 2.94 ± 0.55 | 4.13 ± 0.68 | 5.22 ± 0.58 |
| Depth of first kick (m)*^# | -0.50 ± 0.24 | -0.89 ± 0.18 | -1.04 ± 0.17 |
| Distance of first kick (m)*^ | 6.16 ± 0.57 | 6.62 ± 0.68 | 6.65 ± 0.69 |
| Time of First Kick (s)*^ | 1.96 ± 0.19 | 2.08 ± 0.24 | 2.09 ± 0.24 |
| Time to 5 m (s) | 1.54 ± 0.09 | 1.53 ± 0.08 | 1.53 ± 0.09 |
| Time to 7.5 m (s)*^# | 2.59 ± 0.18 | 2.50 ± 0.16 | 2.48 ± 0.17 |
| Time to 10 m (s)*^ | 3.91 ± 0.29 | 3.82 ± 0.26 | 3.79 ± 0.28 |
| Time to 15 m (s)*^ | 6.62 ± 0.40 | 6.54 ± 0.37 | 6.56 ± 0.42 |
| Avg. Vel. 0-5 m ($m \cdot s^{-1}$) | 3.26 ± 0.19 | 3.27 ± 0.17 | 3.27 ± 0.18 |
| Avg. Vel. 5 -7.5 m ($m \cdot s^{-1}$)*^ | 2.41 ±0.24 | 2.60 ± 0.23 | 2.67 ± 0.25 |
| Avg. Vel. 7.5 -10 m ($m \cdot s^{-1}$) | 1.91 ± 0.17 | 1.92 ± 0.16 | 1.92 ± 0.18 |
| Avg. Vel. 10 - 15 m ($m \cdot s^{-1}$)^# | 1.85 ± 0.10 | 1.84 ± 0.09 | 1.81 ± 0.11 |

*Significant difference between Dive 1 and Dive 2, ^Significant difference between Dive 1 and Dive 3, #Significant difference between Dive 2 and Dive 3

There were also significant main effects between each dive type for time to 15 m ($F_{2,150} = 7.62$, $p = 0.001$). Dive 1 was significantly slower than Dive 2 (difference in mean, 95 % confidence intervals, *p* value) (0.08 s, 0.03 to 0.13, $p = 0.001$) and Dive 3 (0.06 s, 0.01 to 0.12, $p = 0.01$). This was similar for time to 10 m ($F_{2,150} = 29.86$, $p < 0.001$), with Dive 1 also being slower than Dive 2 (0.09 s, 0.05 to 0.13, $p < 0.001$) and Dive 3 (0.12 s, 0.08 to .15, $p < 0.001$) regardless of gender. There was no significant main effect for time to 5 m ($F_{2,150} = 0.753$, $p < 0.001$). The significant pairwise comparisons of each parameter are displayed in Table 11.

**7.5 Discussion**

Previously, there have been no studies that have compared underwater trajectories using the Omega OSB11 block and kick-start technique. Through comparing three common underwater trajectories this study found that the trajectory which produced the fastest start performance is one that is deep enough to reduce the effects of drag while still enabling the swimmer to travel in the desired horizontal direction.

The trajectory utilised in each dive condition changed the total amount of time spent underwater. The significant differences between total time spent underwater between each of the dive types was a result of significant differences between breakout time and breakout distance. Changing the total time spent underwater would affect the amount of resistance acting to slow the swimmer. Consequently, the slower average velocities between 5-7.5 m and slower split times (5, 7.5, 10, 15 m) for Dive 1 could be due to increased resistance acting on the swimming and commencing free swimming earlier. These findings are similar to Lyttle and Blanksby (2000) and Lyttle et al. (1998) who examined the underwater phase of a turn and found that a swimmer can travel faster underwater than over water due to increases in drag forces present when the swimmer is travelling at the surface. Therefore, spending longer underwater does not mean that Dive 3 would necessarily be the fastest dive; as Cossor and Mason (2001) suggest. Dive 3 was only marginally faster than Dive 1. This is mainly because during this dive the swimmer is spending longer travelling down rather than in the desired horizontal direction, which can explain the significant difference in average velocity between 10-15 m as Dive 3 would have spent a larger portion of this section underwater while Dive 1 was free swimming

Furthermore, there were no significant differences between dive conditions for average velocity during the 7.5 – 10 m segment, however there were differences in the segment before (5-7.5 m) and after (10 – 15 m). Dive 1 would have been fully surfaced and free swimming during this segment, while Dive 2 and Dive 3 would have been in the underwater phase, but presumably at different depths. It is likely, that during this segment Dive 2 and Dive 3 would experience a larger deceleration than Dive 1 due to the increase in resistance just below the surface of the water and more propulsion being able to be created through free swimming. Consequently, the higher velocities achieved in the 5-7.5 m segment by Dive 2 and 3 are negated during the 7.5-10 m segment due to Dive 1 free swimming while Dive 2 and Dive 3 were still underwater. Therefore, the velocity achieved by the swimmer during the start phase is not purely a result of the underwater phase, there are other parameters such as free swimming velocity that would affect overall performance.

The maximum depth achieved during the underwater phase would also significantly affect overall start performance. The depth the swimmers are travelling at would have an effect on the amount of drag acting on the swimmer and in turn would affect the velocity of the underwater phase. Hence, the differences between maximum depth most likely resulted in differences in average velocity between 5-7.5 m and time to 7.5 m for each condition. As the swimmers are also able to maintain a higher velocity for longer using Dive 2 and Dive 3 it would suggest that if the swimmer travels at greater depths below the surface they are able to avoid unnecessary wave drag forces, reduce the total resistance acting on them and maintain a higher velocity for longer. Lyttle et al. (1998) examined the optimal gliding depth for a swimming turn and found that there were large reductions in drag the deeper the swimmer travelled. However, Lyttle et al. (1998) did not directly measure wave drag or use depths deep enough to mimic the swimming start. More research is needed to determine how wave drag acts on the swimmer during the underwater phase of the swimming start.

Starting the first kick earlier would mean the swimmer is in the glide phase for a shorter amount of time, which would also increase resistance during the underwater phase.. These results support the recommendation that swimmers should hold their glide for longer in order to maintain the speed generated in the first two phases of the start (Houel et al., 2012; Naemi et al., 2010; Thow et al., 2012). For Dive 1 swimmers commenced their first kick significantly earlier as they were aiming to resurface as fast as possible. This reduced the glide time and increased hydrodynamic resistance that would result in speed loss (Elipot et al., 2009). This speed loss can explain the lower velocity exhibited between 5-7.5 m for Dive 1 and a slower time to 5, 7.5, 10 and 15 m respectively. Beginning kicking earlier may also be less efficient as the swimmer requires more energy during free swimming at the surface than is required performing undulatory kick below the surface, due to increased drag forces acting on the swimmer at the surface (Lyttle et al., 1998). If a swimmer is able to hold a streamlined position and glide for longer they are able to maintain a higher velocity with no extra energy cost (Lyttle & Blanksby, 2000; Thow et al., 2012). Naemi et al. (2010) also states that maintaining this position underwater during starts and turns is beneficial as the swimmer is able to travel faster than if the swimmer was kicking. Hence, the timing of the swimmers' first kick after entry would also have implications on the amount of velocity able to be maintained following entry into the water and in turn overall start performance.

The findings from this study are evidence that the trajectory adopted by the swimmer and the timing of first kick would change the amount of time spent underwater and in turn alter the amount of resistance acting on the swimmer. Subsequently, swimmers' can reduce the amount of resistance acting on them by changing the trajectory they are travelling at. They can do this by maintaining the streamlined position for longer during the glide phase before commencing their first kick and optimising the depth that they adopt during the underwater phase. Therefore, to achieve faster starts there is a trade-off between time spent underwater to reduce drag and the maintenance of velocity generated during the first two phases (on-block and flight) of the start.

**7.6 Conclusions**

Three underwater trajectories have been compared in this study. While the differences between each dive condition were small, when working with an elite population these changes are significant and can practically contribute to improving start performance. For example in the 2007 FINA World Swimming Championships the top three finishers in the Men's 100 m Freestyle were separated by only 0.04 s (Hardt, Benjanuvatra, & Blanksby, 2009). Since these margins can be so small, any advantage in reducing race time is important to athletes, coaches and sports scientists. The trajectory used in Dive 2 had the fastest time to 15 m, therefore this was not significantly different to the trajectory used in Dive 3. Dive 1 trajectory was the slowest as swimmers commenced free swimming earlier than all of the other dive types. As a result of this, the velocity generated in the first two phases of the start was not maintained, particularly between the 5-7.5 m segment; due to an increased presence of drag acting on the swimmer.

Thus, swimmers should hold their glide for longer and commence their first kick later in the underwater phase. Specifically, it is recommended swimmers should commence undulatory kick at approximately 6.6 m and achieve a maximum depth of approximately -0.92 m to minimise the velocity lost during the underwater phase. This was the average distance used during Dive 2, so may be used as an early estimate. Commencing free-swimming before this point would result in increased hydrodynamic resistance and reduced velocity as evidenced during Dive 1 where swimmers commenced their first kick earlier. Therefore, additional research investigating the relationship between velocity, depth and drag is needed to further enhance the results of this study and allow for more accurate individual recommendations to be made.

### 7.7 Practical Implications

- The ideal underwater trajectory is a trade-off between time spent underwater and the maintenance of velocity generated during the first two phases of the start.
- Using a shallower trajectory would increase the resistance acting on the swimmer resulting in a reduction of velocity during the underwater phase.
- There is evidence that adopting a trajectory similar to Dive 2 would provide benefits for overall start performance.
- Swimmers should hold their glide for longer and commence their first kick after 6.6 m.

# Chapter 8: How Does Drag Affect the Underwater Phase of the Swimming Start?

## Chapter 8.0 How Does Drag Affect the Underwater Phase of the Swimming Start?

*From:* **Tor, E.,** Pease, D., & Ball, K. (2015). How does drag affect the underwater phase of a swimming start? *Journal of Applied Biomechanics, 31*, 8-12

### 8.1 Abstract

During the underwater phase of the swimming start drag forces are constantly acting to slow the swimmer down. The current study aimed to quantify total drag force as well as the specific contribution of wave drag during the underwater phase of the swimming start. Swimmers were towed at three different depths (surface, 0.5 m, 1.0 m) and four speeds (1.6, 1.9, 2.0, 2.5 $m \cdot s^{-1}$), totalling 12 conditions. Wave drag and total drag were measured for each trial. Mixed modelling and plots were then used to determine the relationships between each towing condition and the amount of drag acting on the swimmer. The results of this study show large decreases in total drag as depth increases regardless of speed (-19.7% at 0.5 m and -23.8% at 1.0 m). This is largely due to the significant reduction in wave drag as the swimmers travelled at greater depth. It is recommended that swimmers travel at least 0.5 m below the surface to avoid excessive drag forces. Swimmers should also perform efficient breakouts when transitioning into free-swimming to reduce the duration spent just below the surface where drag values are reported at their highest.

### 8.2 Introduction

The underwater phase of the swimming start is defined as the instant when the swimmer's head enters the water to when the swimmer resurfaces again to commence free swimming. While, the underwater phase can be further subdivided into the glide and the underwater kicking phases; this study focussed mainly on the glide portion of the underwater phase. The underwater phases are crucial sections to overall race performance because after the dive itself this is the next fastest section of the race (Connaboy et al., 2010). This phase has also been identified as the most decisive in order to achieve faster overall start performances (Cossor & Mason, 2001; Elipot et al., 2009; Thow et al., 2012). The average speed during this phase is highly dependent on horizontal speed at entry and drag forces acting on the subject during the glide phase.

There are three main components of drag or resistance that act on the swimmer as they move through the water; friction (or skin), form, and wave drag (Lyttle et al., 1998; Naemi et al., 2010; Naemi & Sanders, 2008; Sheehan & Laughrin, 1992; Vennell et al., 2006). Frictional drag represents the resistance produced as a result of friction between the water and the surface of the swimmer (Lyttle et al., 1998). Form drag is the result of the differences between pressure at the leading and trailing edges of the body with boundary layer separation from the swimmer being the principal contributor (Naemi et al., 2010).

The third primary component of drag is wave drag, which occurs when swimming at or near the surface of the water. Wave drag is considered the most deleterious of all the types of drag as it has been shown to increase at a rate of up to the $6^{th}$ power of speed, compared to linear and squared relationships for friction and form drag respectively (Lyttle et al., 1998; Vennell et al., 2006). Wave drag is mainly caused by energy lost in creating wave systems around the vessel or swimmer (Vennell et al., 2006). Research has found that wave drag contributes anywhere between 5-45% of the total drag force at speeds of 2 $m \cdot s^{-1}$ when swimming at the surface. However, this number is significantly lower when swimming at a depth of 0.6 m (Vennell et al., 2006). By directly measuring the contribution of wave drag it would be possible to further refine earlier work and provide better recommendations for athletes (Lyttle, Blanksby, Elliott et al., 1998; Pease, 2010; Pease & Vennell, 2011; Vennell, Pease, & Wilson, 2006).

Towing swimmers through the water at various velocities in a streamlined position is a common way to determine passive drag in swimmers (Clarys, 1979; Lyttle et al., 1998). Although, there have been conflicting results reported in pervious literature. Lyttle et al (1998) reported 10-20% decrease in the drag force when travelling at 0.4 m - 0.6 m deep respectively relative to gliding at the surface and 7-14% reduction when gliding at 0.2 m deep. In another study Maiello et al. (1998) found a higher drag force at the water surface. Conversely, Jiskoot and Clarys (1975) used a test re-test design and reported that swimmers experienced 21% higher drag values after the initial test and 20% higher drag after the retest while travelling 0.6 m below the surface compared to swimming at the surface. This may have been because Jiskoot and Clarys (1975) used speeds that were slower than those produced by swimmers in competition (1.5-1.9 $m \cdot s^{-1}$), particularly during the start phase. Therefore, the results from Jiskoot and Clarys (1975) did not appear to reflect the contribution of wave drag when travelling near the surface. Consequently, separating the measurement of total drag and wave drag would allow for a more precise measurement of passive drag and provide valuable information about the contribution of wave drag to total drag during the underwater phase of the swimming start.

In a study which did separate the measurement of wave drag, Vennell et al. (2006) found that swimmers should travel 1.8 chest depths below the surface at 0.9 $m.s^{-1}$ and 2.8 chest depths at 2.0 $m.s^{-1}$ to avoid significant wave drag. However, Vennell et al. (2006) did not use human subjects, instead they towed mannequins in the supine position. Even though drag values would be the same in the prone position, using mannequins instead of human swimmers is likely to alter resulting drag forces due to friction drag and small positional changes not occurring as would be the case with human subjects. Further, Lyttle et al. (1998) towed experienced male swimmers in a streamlined position along the length of a 25 m pool at four different depths (0.6 m, 0.4 m and 0.2 underwater and at the water surface) and six speeds ranging from 1.6 to 3.1 $m \cdot s^{-1}$, in 0.3 $m \cdot s^{-1}$ increments. Total drag force was measured for each condition. From their results it was concluded that swimmers should perform their glides at approximately 0.4 to 0.6 m underwater to achieve a reduction in drag for velocities above 1.9 $m \cdot s^{-1}$. Hence, the current study would expand on these findings by quantifying wave drag directly and relating it to the swimming start.

Wave drag research in swimming is scarce largely due to methodological difficulties in obtaining direct measurements of the component drag forces. Most of the wave drag literature is focused largely on aquatic animals and ships (Hertel, 1969; Kelvin, 1887). While these findings might transfer to human swimmers, aquatic animals and ships can achieve much higher velocities than human swimmers. In addition, movement and shape also differs, so the extent of this transfer is unclear. Hence, there are a number of methodological aspects used in this study that were novel and allow for more accurate estimation of wave drag in the future. This study applied the longitudinal wavecut method (LWC) to directly approximate wave drag. The LWC is described in Eggers et al. (1967) and is based on research on wave resistance around ships. This method involves the measurement of one or more wave profiles along a straight track parallel to the direction of motion for the ship or vessel (Eggers et al., 1967). This method can be applied to swimming as a swimmer travelling through water essentially follows the same hydrodynamic principles as a ship out at sea. Toussaint (2006) has previously used this method in conjunction with the Measurement of Active Drag (MAD) system to measure wave drag during active swimming.

The aim of this study was to investigate how drag affects the swimmer during the underwater phase of the swimming start. This study would also determine how the contributions of wave drag change with varying depths and speeds. It was hypothesized that reducing wave drag during the underwater phase of the swimming start would reduce total drag and produce a slower rate of deceleration resulting in a faster start time. This would be useful particularly when swimmers rise towards the surface and transition into free swimming where a reduction in drag would lead to the maintenance of higher velocities throughout the underwater phase. It was further hypothesised that wave drag would have a larger contribution to total drag as the swimmer travels at faster speeds closer to the surface.

## 8.3 Methods

### 8.3.1 Subjects

Sixteen swimmers participated in this study; 11 were male and 5 were female (aged 20 ± 2 y, 78.05 ± 9.01 kg weight and 1.83 ± 0.07 m height). All swimmers were Australian Institute of Sport (AIS) Swimming Scholarship Holders and had at least five years of competitive experience at the National level. Of the 16 swimmers, three swimmers were Olympians and two were World Championship representatives.

### 8.3.2 3D Laser Scanning

Prior to pool testing each swimmer was full-body laser scanned using a 3D laser scanner (VITUS$^{smart}$XXL, Wiesbaden, Germany). Five scans were completed for each swimmer (See Appendix III for diagram). The first two scans were completed in standard positions used for anthropometry. The subsequent scans were swimming specific, the first was in a standing streamline position, the second was kneeling in a streamline position and the third position was done so that the swimmer was on their back with their feet pointed in the air. These positions were chosen to mimic aspects of the streamline position adopted by most swimmers during the underwater phase of a swimming start. Following this the swimming specific scans were processed and stitched together so that total body surface area and total body length in a streamline position were able to be determined for incorporation into the wave drag calculations. Scans were all completed on the same day as testing in the pool to minimise changes to body shape that can occur throughout a swimming season.

### 8.3.3 Towing Protocol

Swimmers were towed along the length of a 3 m deep, 25 m pool at maintained depths of 0.0 m (surface), 0.5 m and 1.0 m at velocities of 1.6 $m \cdot s^{-1}$, 1.9 $m \cdot s^{-1}$, 2.0 $m \cdot s^{-1}$ and 2.5 $m \cdot s^{-1}$ resulting in 12 conditions in total. The surface depth condition was defined as the depth of the midline when the swimmers' back broke the surface of the water. The 0.5-1.0 m conditions were also aligned with the midline of the body at their respective depths. Similar methods have been used in multiple studies (Lyttle, Blanksby, Elliott, & Lloyd, 1999; Lyttle, Blanksby, Elliott, & Lloyd, 2000; Lyttle, Blanksby, Elliott et al., 1998; Sheehan & Laughrin, 1992),although these studies used slightly faster velocities. The fastest speed chosen for this study was 2.5 $m \cdot s^{-1}$ because this was the maximum speed which could be accurately achieved by the dynamometer used in the study. While this is a speed typically adopted by the swimmer during the turn, the same principles can theoretically be applied to the start as well. Further, this speed was adequate because the average underwater speed reached by elite swimmers during a start (after the initial entry velocity) is 2.38 $m \cdot s^{-1}$ (Tor, Pease, et al., 2014).

In order to assess if subjects were achieving the prescribed depth for each trial, a video camera feed which was displayed on a calibrated screen was used to visually monitor each subject's depth. The swimmer's depth was defined as the longitudinal axis of the swimmer while in the streamlined position (Lyttle et al., 1998). Swimmers were given three practice tow trials at each depth at 1.6 m·s$^{-1}$ to ensure that they were able to maintain each depth prior to testing. During the towing trials, swimmers were also provided with verbal feedback as needed to ensure that the correct depths were maintained. A threshold of ≈ 0.1 m was allowed from the set depth as the deeper conditions were hard to maintain particularly at lower speeds. If the desired depth was not maintained throughout the full tow, the trial was deemed incorrect and the trial was repeated. Although, most swimmers were able to maintain the required depths after their practice trials

**Figure 9 Dynamometer used for towing**

Swimmers wore textile-training swimsuits and were towed using a dynamometer towing device to measure the total drag force (Figure 9). The speed of each tow was controlled by a dynamometer consisting of an electronic drive attached to a 20 cm diameter metal drum around which a 2 mm nylon rope was wound.  The rope was intertwined in the subject's fingers while in the traditional streamlined position allowing them to be towed in a controlled manner. A pulley was positioned at the depth of each tow, i.e. at the water surface for surface tows, 0.5 m below the surface of the water for tows at 0.5 m, 1.0 m for 1.0 m tows. A similar method of towing was used in previous research (Formosa, Mason, & Burkett, 2011; Formosa, Sayers, & Burkett, 2012).

Wave drag is only a portion of the total drag experienced by the swimmer travelling through the water and therefore it cannot be determined directly from towing-force measurements and additional estimations are needed (Eggers et al., 1967). To approximate wave drag, four acoustic proximity sensors recording at 100 Hz were used. The sensors were mounted approximately 0.9 m above the pool surface and 1.0 m parallel to the midline of the swimmers' expected trajectory. The sensors provided a water surface map which could then be analysed using the Longitudinal Wave Cut (LWC) method (Eggers et al., 1967).

### 8.3.4 Drag Calculations

To initiate data collection a trigger was activated as the swimmers' head approached the first acoustic sensor and recorded for 30 seconds. The data was collected simultaneously from the dynamometer and acoustic sensors using the computer software LabChart Pro by Ad Instrument (Sydney, Australia). Total drag was able to be determined using the information from the dynamometer. Wave drag calculations were conducted in Matlab utilising a code based upon previous research (Eggers et al., 1967). The value of wave drag for each trial was represented by a mean of the four sensors and it was assumed that wave forms on both sides of the body were symmetrical.

### 8.3.5 Statistical Analysis

Descriptive statistics were calculated for total drag and wave drag for each towing condition. A number of drag-speed curves were also plotted for visual inspection using means and 95% confidence intervals for each towing condition. The percentage decrease in total drag and wave drag was also determined between the surface and each towing condition.

Mixed modelling was used to determine the differences between each of the towing conditions. Before the data was modelled, each towing condition was coded (Speed: 0 = 1.6 $m \cdot s^{-1}$, 1 = 1.9 $m \cdot s^{-1}$, 2 = 2.0 $m \cdot s^{-1}$, 3 = 2.5 $m \cdot s^{-1}$, Depth: 0 = surface, 1 = 0.5 m and 2 = 1.0 m) and a new variable was created to represent the interaction between depth and speed (depth x speed). The fixed factors were speed and depth while the random effects were the subjects themselves. An interaction was also added between speed and depth to determine how drag was affected by both of these factors. Estimated mean effects were compared between each condition using pairwise comparisons with a Bonferonni correction. Significance was set at $p < 0.05$ and models were completed using total drag and wave drag as separate dependent variables. All analyses were completed using IBM SPSS Statistics Package (Version 19.0, SPSS, Chicago, IL).

## 8.4 Results

There was a clear increase in total drag as speed increased for all conditions (Figure 10). The same trend was displayed for both the 0.5 m and 1.0 m conditions. While at the surface there was a large increase in drag particularly when velocity increased above 1.9 $m.s^{-1}$. In addition, for total drag there were decreases regardless of speed as the swimmer travelled at 0.5 m and 1.0 m relative to total drag at the surface (Figure 13). The largest percentage decrease in total drag from the surface is at 2.5 $m \cdot s^{-1}$, there is a -19.8% reduction at 0.5 and -23.8% reduction at

1.0 m below the surface. Mixed Modelling was able to support these findings by revealing that there were significant main effects for depth ($F_{2,165}$ = 103.61, $p$ < 0.001) and speed ($F_{3,165}$ = 1591.45, $p$ < 0.001) individually. There was also a significant main effect for the interaction between depth and speed ($F_{6,165}$ = 31.23, $p$ < 0.001).

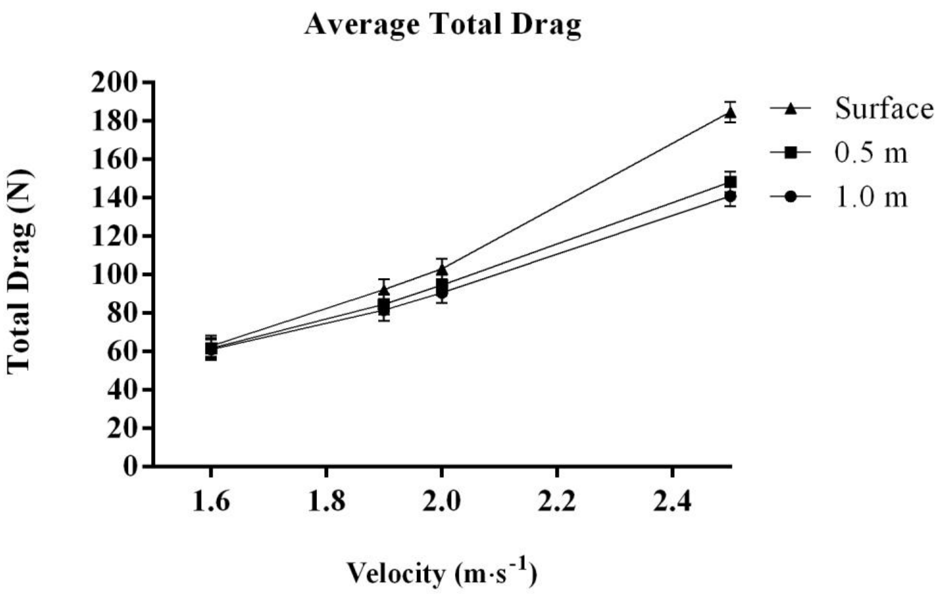



**Figure 10 Average total drag for each towing condition.**

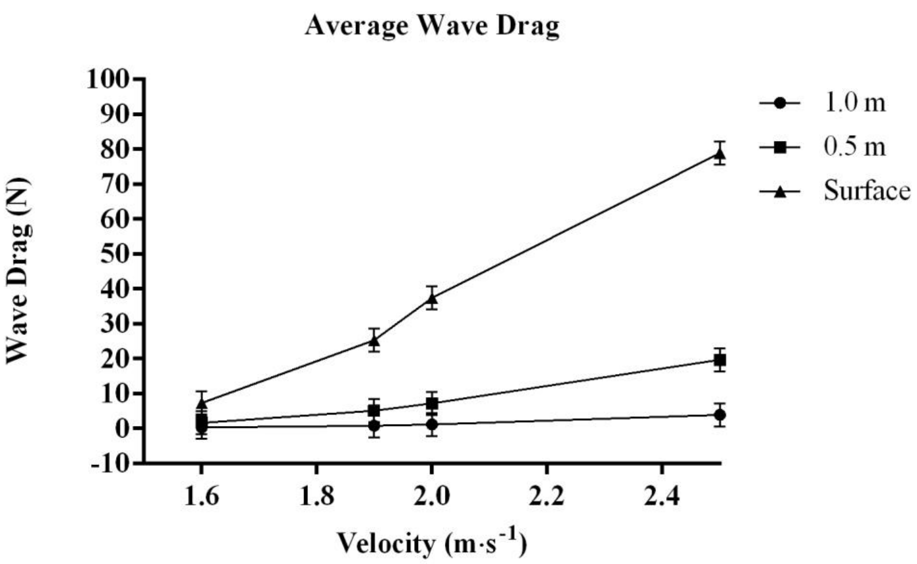



**Figure 11 Average wave drag for each towing condition.**

The wave drag magnitude was always greatest for the surface condition (Figure 11). Wave drag was minimal for the 1.0 m condition across all velocities. There were also large increases for the surface condition as speed increased. Moreover, when travelling 0.5 m below the surface there is at least a 70% decrease in wave drag for all velocities when compared to the surface (Figure 12). At 1.0 m below the surface there is nearly a 100% decrease in wave drag for all velocities. Mixed modelling for wave drag also showed that there were significant main effects for depth ($F_{2,165}$ = 544.21, $p$ < 0.001) and speed ($F_{3,165}$ = 201.03, $p$ < 0.001). A significant main effect also existed for the interaction between depth and speed ($F_{6,165}$ = 87.71, $p$ < 0.001).

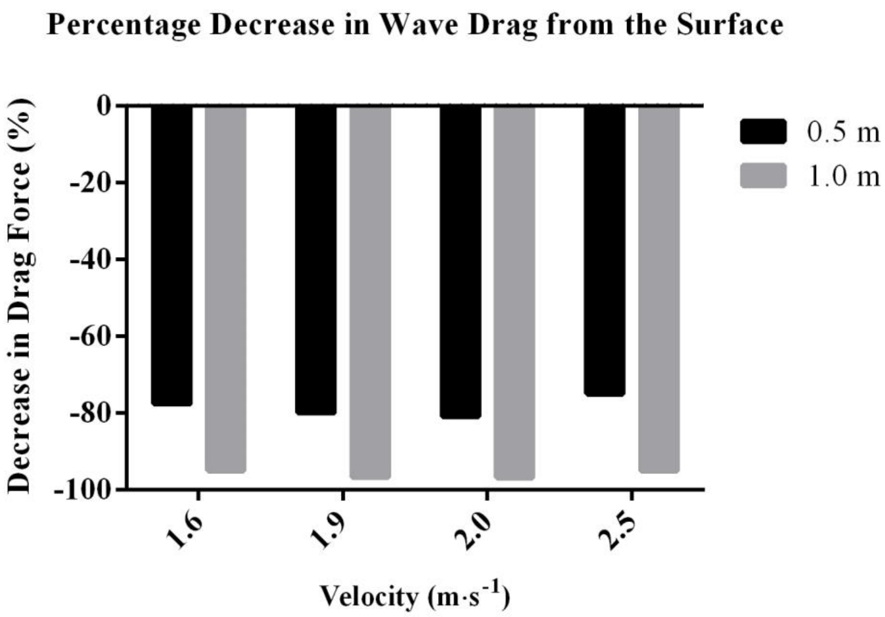



**Figure 12 Percentage decrement in wave drag from the surface recorded at 0.5 m and 1.0 m below the surface.**

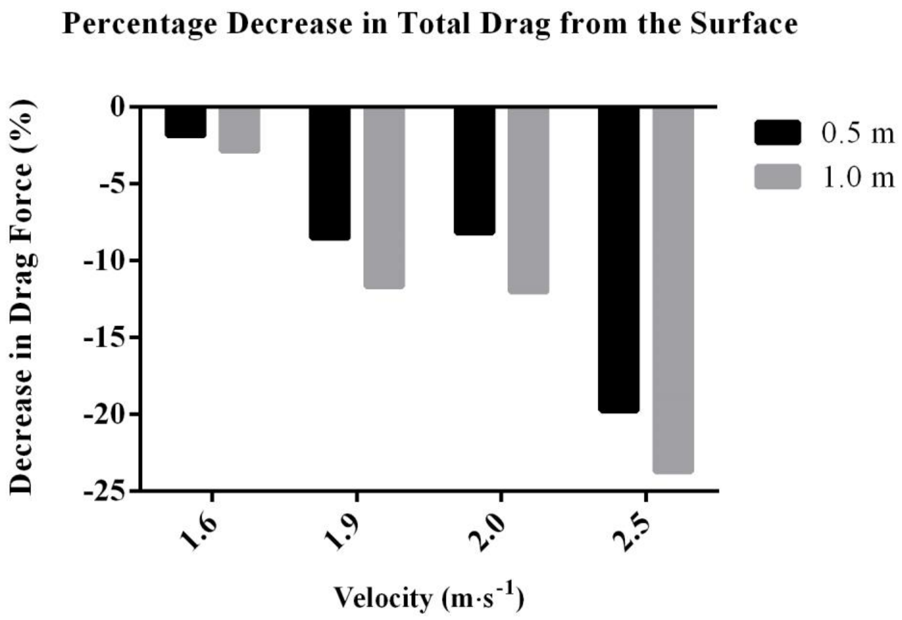



**Figure 13 Percentage decrement in total drag from the surface recorded at 0.5 m and 1.0 m below the surface.**

**8.5 Discussion**

This was one of only a few studies to approximate wave drag using human swimmers and aimed to investigate the relationship between drag, speed and depth. The results of this study support the hypothesis of wave drag increasing its contribution to total drag measurements as speed increased and as the swimmer travelled closer to the water surface. With these findings recommendations have been made on the depth swimmers should travel during the underwater phase of the swimming start to reduce the amount of drag acting on them.

There have been a number of similar studies which have observed increases in passive drag with speed (Alley, 1952; Jiskoot & Clarys, 1975; Karpovich, 1933; Lyttle, Blanksby, Elliott et al., 1998). Regardless of depth the amount of total drag increased in this study with speed, with the greatest increases in total drag at speeds above 1.9 $m{\cdot}s^{-1}$. As swimmers are likely to be travelling above speeds of 1.9 $m \cdot s^{-1}$ during the underwater phase of the swimming start it is important to determine ways to decrease total drag under those conditions.

A strategy to reduce total drag would be to travel well below the surface of the water. The value of total drag is reduced as the swimmer travels deeper underneath the surface of the water. In fact this study found an 8-24% decrease in drag at speeds above 1.9 $m \cdot s^{-1}$ when the swimmer is travelling 0.5-1.0 m below the surface respectively. Lyttle et al. (1998) also found a 10-20% decrease in drag forces when travelling at 0.4-0.6 m depths relative to gliding at the water surface and a 7-14% reduction when gliding at 0.2 m. Consequently, the large increases in total drag displayed as the swimmer travels closer to the surface in this study are likely due to the increased contribution of wave drag. This suggests that swimmers need to be mindful of travelling at the surface particularly during the breakout and transition from the underwater phase to free-swimming during the start.

Analogous to total drag, the speed the swimmer is travelling at would also impact on the amount of wave drag acting on the swimmer. When specifically investigating wave drag and speed, it is clear that there are large increases as towing speed increases. Wave drag was apparent for all speeds at the surface with only a small amount present at the slower speeds. This is similar to Jiskoot and Clarys (1975) who reported low levels of total drag at speeds of 1.6-1.9 $m \cdot s^{-1}$, which is evidence to suggest that wave drag does not have a substantial contribution to total drag until speeds are higher than 1.6 $m \cdot s^{-1}$. The results from the present study support this as there was a significant interaction between wave drag, depth and speed. Further, there were sharp increases in wave drag as speed reached above 2.0 $m \cdot s^{-1}$. This was true for all depths except for 1.0 m below the surface. Consequently, this study showed that wave drag changes with speed but is highly dependent on the depth. This is because as the body moves close enough to the surface of the water for the distorted flow to impinge on the surface there are pressure changes due to the Bernoulli Effect. These pressure changes cause depressions and elevations in the water's surface around the body which then cause wave drag.

The influence of depth on wave drag was investigated by Vennell et al. (2006) who towed mannequins in a water treadmill or 'flume' and found wave drag to be negligible at a depth of 0.6 m underwater. The near 100% decrease in wave drag when the swimmers' travelled 1.0 m below the surface in the current study shows that at this depth wave drag is negligible. Consequently, when relating this finding directly to the underwater phase of the swimming start, the depth the swimmer chooses would affect the amount of wave drag and in turn significantly affect the amount of total drag acting on them. Thus, swimmers should reduce the time spent travelling at depths between 0.5 m and the surface to decrease the amount of wave drag acting on them.

Moreover, the changes in drag values for the below surface conditions between 1.6 $m.s^{-1}$ and 1.9 $m.s^{-1}$ differ slightly from that of Vennell et al. (2006). A possibility for this variance is that this study used human subjects rather than mannequins like that used by Vennell et al. (2006). A limitation of using human subjects is there are natural positional changes in the horizontal and vertical plane, which can occur when towing the swimmers through the water. These subtle positional changes would change the angle of attack and consequently alter the value of frontal area. As a result of this there would be changes in the value of total drag as well as changes in relative contribution of each drag component (Pease & Vennell, 2011). Pease and Vennell (2011) found that a slight positive angle of attack would cause a much greater contribution of wave drag to total drag due to an earlier separation of flow which disturbs a greater water mass. However, slight changes in the angle of attack while the swimmer was in the glide position may have resulted in an over estimation of drag, particularly at lower speeds. Hence, the effects of depth on wave and total drag far outweighs those of changing the angle of attack (Pease & Vennell, 2011). Furthermore, as these changes in position occur naturally during swimming and are hard to control/measure when towing human swimmers with minimal equipment, the variance in drag to previous studies does not significantly alter the main findings of this study.

A reduction in wave drag is important during the underwater phase of the swimming start, as this is the most deleterious form of drag experienced by the swimmer. A reduction in wave drag would translate directly to an improvement in start performance for the same initial conditions of speed and angle of water entry. Theoretically, travelling below 1.0 m would be ideal; although, some swimmers may not be able to maintain this depth and would lose speed due to poor underwater kicking ability. Therefore, even though the ideal underwater trajectory is individual it is still an optimisation between not travelling too deep where there is no advantage in wave drag reduction and minimal distance that would produce an efficient breakout (Tor, Pease, & Ball, 2014).

The results from this study can be used practically to make recommendations on the depth swimmers should use during the underwater phase of the swimming start to reduce the amount of wave drag acting on them. Even though the maximum speed used to tow swimmers was 2.5 $m \cdot s^{-1}$, the findings from this study can still be applied to the speeds used during the underwater phase of the swimming start. Earlier research by Tor, Pease, et al. (2014) found that elite swimmers can maintain underwater velocities of 2.38 $m \cdot s^{-1}$ throughout the underwater phase and at this speed there is an 80% decrease in wave drag when below 0.5 m. Consequently, swimmers should travel deeper than 0.5 m under the surface for as long as possible to reduce the effects of drag, in particular the wave drag component. Although, the findings from this study would specifically relate to the glide phase of the underwater sub-phase of the start, as the swimmers were towed in the passive streamlined position, the same principles and recommendations can be applied to the entire underwater phase of the start and turn. Swimmers should also perform efficient breakouts when transitioning into free-swimming to reduce the duration spent just below the surface where drag values are reported to be at their largest.

# Chapter 9: Can Biomechanical Feedback be used to Change the Underwater Trajectory of a Swimming Start?

# Chapter 9.0 Can Biomechanical Feedback be used to Change the Underwater Trajectory of a Swimming Start?

## 9.1 Abstract

Adopting an individually optimised underwater trajectory in swimming can reduce resistance and lead to better start performance. This study aimed to determine if quantitative biomechanical feedback could be used to change the underwater trajectory of the swimming start. Three elite freestyle swimmers participated in a six-week test-retest-retention test study. Following the pre-test a target parameter was assigned to each swimmer to focus upon during the intervention period. Two subjects focused on their breakout distance while the third subject focused on the distance of their first kick. Precise biomechanical feedback detailing the distance adjustment required and video from a specialised kinematic analysis system was provided. During the intervention, feedback was faded to facilitate exploration of functional movement solutions. Comparative individual-based analysis using performance curves revealed that subjects were able to make rapid changes to their underwater trajectory during the early stages of the intervention. Two subjects were able to retain the changes to their technique, although this only transferred to improvements in performance for one swimmer. Precise quantitative augmented feedback can be used to change a swimmers underwater trajectory; however given the complex nature of the swimming start the effects on overall performance require further investigation.

## 9.2 Introduction

In sport it is commonplace for a coach to provide external feedback regarding an athlete’s performance, ranging from stop watch timing, to verbal cueing or video feedback. However, the link between feedback provision, skill learning and biomechanics, particularly in applied settings has not been widely explored (see Baudry et al. (2006) and Thow et al. (2012) for exceptions). This is surprising considering it is apparent that the biomechanics and skill acquisition disciplines would complement each other to form a holistic approach to complex skill learning (Portus & Farrow, 2011). By combining aspects of biomechanics and skill acquisition to the swimming start this study would be able to provide a practical method for complex skill learning.

The learning or refinement of a complex motor skill is moderated by the learner's sensory modalities which provide intrinsic feedback. The use of external augmented feedback is suggested to be particularly important in environments where intrinsic feedback is low or difficult to interpret, such as swimming or gymnastics (Baudry et al., 2006). Augmented feedback provides supplementary information about a skill to complement the information provided by his/her sensory system. A common feature in high performance sport programs is the provision of augmented feedback derived from biomechanical analysis (Phillips et al., 2013). The selection of measurable parameters for the provision of augmented biomechanical feedback to athletes is important to enhance sport specific skill learning (Phillips et al., 2013). According to Phillips et al. (2013) selection of target biomechanical parameters should be based on three criterion; the variables should be key to performance improvement, must be able to be adjusted by the athletes and the variable be able to be measured reliably. Yet, there is very little empirical evidence regulating how practitioners can best utilise such information (Abernethy et al., 2008). Further, a predominant feature of past feedback research is that many have examined simple laboratory tasks, which are unlikely to relate to complex motor skills such as those used in most sports (Wulf & Shea, 2002; Young & Schmidt, 1992).

A typical example of how augmented feedback has been used in a sport setting is provided by Smith and Loschner (2002) who investigated how biomechanical feedback can be used to improve rowing performance. They instrumented two different boats and found that feedback provided about the forces generated by the rower were most effective in improving rowing performance; suggesting that this type of immediate feedback is essential for learning as it provides athletes with the opportunity for exploration. This augmented feedback principle has previously been referred to as the guidance hypothesis (Salmoni et al., 1984); using this hypothesis, feedback is suggested to have a large influence on learning by assisting the learner to guide or direct performance when feedback is present. However, there is currently some debate in the literature as to the generalizability of this hypothesis as many of the studies examining the guidance hypothesis have typically not utilised complex motor skills (Phillips et al., 2013).

In a rare study examining elite performers, Baudry et al. (2006) studied skilled gymnasts to determine if concurrent auditory feedback could be used to improve body alignment during the pommel horse circle, a complex skill that provides intrinsic information which is difficult for a performer to utilise effectively. After two weeks of training the concurrent feedback group were able to improve their body alignment by 2.3%. Conversely, Broker, Gregor, and Schmidt (1993) found that concurrent kinetic feedback of cycling performance did not improve performance or learning compared to a summary feedback group. This suggests results may differ depending on whether feedback was given on the outcome of the movement (often referred to as knowledge of results) (Broker et al., 1993) or on biomechanical process measures (referred to as knowledge of performance) (Baudry et al., 2006). Furthermore, results may be influenced by the type of movement being practiced. Both Baudry et al. (2006) and Broker et al. (1993) examined continuous cyclical movements rather than a discrete skill such as a swimming start.

Specific to swimming, Thow et al. (2012) and Sanders (1995) used complex swimming skills and found that with verbal and video feedback swimmers where able to change their technique. Using a similar feedback methodology to the current study, Thow et al. (2012) used specialised computer software called GlideCoach to provide feedback on glide performance. Subjects were randomly split into three groups, one group was provided just video feedback, another group was provided video and verbal feedback while the final group was given video feedback and information from GlideCoach during the four week intervention period. Following a retention test it was determined that information regarding postures, initial velocity, glide factor and average velocity provided by GlideCoach was effective for initial learning, retention and application of gliding skills compared with other feedback methods. This may have been because GlideCoach was able to deliver both knowledge of results and knowledge of performance feedback to the swimmers. Thow et al. (2012) however, only included five testing sessions in their study design and used a group-based approach, which may not have accounted for individual differences in rate of learning and perception of feedback.

The scheduling of feedback provision also influences learning (Young & Schmidt, 1992). How frequent the feedback is provided has been demonstrated to influence how the learner values sources of task-intrinsic feedback or engages in important aspects of action planning that are essential to movement task success (Magill & Anderson, 2012; Young & Schmidt, 1992). When evaluating learning using a retention test design, researchers have revealed that increased feedback frequency can degrade rather than facilitate learning. In these examples, the over-saturation of augmented feedback led to learners developing an over-reliance on this modality as they neglected the usefulness of their own intrinsic feedback. Therefore, researchers advocate that once a skill is adequately learned or refined; practitioners should adopt fading feedback schedules (Magill & Anderson, 2012). Gradually removing feedback from learning environments encourages the learners to maintain their reliance on intrinsic learning (Wulf & Schmidt, 1994). However, these principles may not apply to all tasks, particularly more complex tasks because these skills usually require a lot more spatial and temporal coordination of various sub-movements and therefore the principles derived from simple tasks may not relate to the learning of more complex skill (Wulf & Shea, 2002).

When assessing the link between augmented feedback and skill learning it is important to examine performance throughout the intervention for greater insight. The changes exhibited during the early intervention stages are often referred to as “maladaptive short-term corrections” (Wulf et al., 1998). These changes are effective in the short term for changing movements to achieve a certain goal, however as the subject becomes reliant on augmented feedback long term performance changes are sometimes not exhibited. Previously, adaptive changes to augmented feedback have rarely been investigated with skilled performers over a long period of time. To investigate this in more detail the current study adopted an individual-based analysis approach, by utilising individual performance curves to describe the learning effect of augmented feedback (Magill, 2007). This approach previously implied examining only one subject and performing analysis within that subject (Ball & Best, 2012). Although, recent work has adopted multiple single subject design, where a number of subjects results have been analysed individually (Kinugasa, 2013). This approach has shown to be particularly effective in uncovering information regarding elite performance, where small differences can be masked using a group-based approach and has been used on multiple occasions in a skill acquisition setting (Ball & Best, 2012; Ball, Best, & Wrigley, 2003; Barris, Farrow, & Davids, 2014)

The swimming environment provides a useful setting to examine the nature of feedback provision when learning a complex skill with limited intrinsic feedback. Swimming starts have been shown to contribute between 0.8 – 26.1% of total race time in competitive swimming (Cossor & Mason, 2001). The swimming start is typically broken into three sections; the on-block, flight and underwater phases (Cossor & Mason, 2001). As the swimmer spends the longest time in the underwater phase (Tor, Pease, et al., 2014), optimising this phase of the swimming start by adopting an individually optimised underwater trajectory would reduce the amount of resistance (drag) acting to slow the swimmer down. This reduction in drag would allow the swimmer to maintain a higher velocity for longer and therefore lead to improved start performances. Consequently, if biomechanical feedback can be used to guide the swimmer to their ideal underwater trajectory they would be able to achieve better starts and as a result achieve better competition results.

The aim of this study was to determine if specific instruction in the form of biomechanical feedback could be used to change the underwater trajectory of the swimming start in elite swimmers. A test-retest study design including a retention condition was used to differentiate between temporary changes and permanent changes in skill performance. An individual-based analysis approach was also used with subjects expected to experience large variations in performance early in the intervention before stabilising during the later stages of the intervention.

## 9.3 Methods

### 9.3.1 Subjects

Three subjects (1 male, 2 female, 18 ± 3 y) were recruited from the Australian Institute of Sport (AIS) Swimming Program to participate in the study. The subjects were considered elite performers with a FINA point score of 750 and above for their main event. The FINA points table assigns point values to swimming performances, the base times are determined every year dependent upon the average top 10 performances worldwide, with the highest possible score being 1000 (FINA, 2010). The experimental design was approved by the AIS Performance Research Ethics Committee and subjects gave informed consent prior to testing.

### 9.3.2 Equipment

Each dive trial was recorded using the Wetplate Analysis System and start time was defined as the time between the start signal and 15 m. The Wetplate Analysis System is a proprietary system developed by the AIS Aquatic Testing, Training and Research Unit (ATTRU) and consists of an instrumented starting block with the same dimensions as the Omega OSB11 starting block (that is used at all major international competitions) and a series of high-speed cameras (Mason et al., 2012). The reliability of the parameters measured was established in an earlier study (Tor, Pease, & Ball, 2014, 2015). The instrumented start block consisted of a Kistler force platform (Z20314, Winterthur, Switzerland) angled at 10°, two Kistler tri-axial transducers (9601A) to measure grab force and an inclined kick plate with four tri-axial transducers (9251A). All force data were collected at 500 Hz and filtered using a 10 Hz low pass Butterworth filter.

Performance time was measured using a second proprietary system, ‘Swimtrak’, which is comprised of seven analogue video cameras recording at 50 hz (Samsung, SCC-C4301P) located perpendicular to the plane of motion at 0 m, 5 m, 7.5 m, 10 m, 15 m, 20 m and 25 m and positioned approximately 5 m above the surface of the pool and 3 m perpendicular to the edge of the pool. The time intervals were recorded as the centre of the swimmer’s head passed through the given distances. The average velocities were calculated for each segment using the formula distance over time. Additional kinematic parameters; maximum depth, breakout distance and time of first kick were determined by digitising the subjects' head at each of the points respectively.

### 9.3.3 Pre – intervention testing

Before the acquisition phase commenced all subjects performed six maximum effort dives (freestyle stroke) in an afternoon test session to determine the characteristics of their current underwater trajectory. Following this, one target parameter of the underwater phase was chosen for each swimmer to focus upon during the acquisition phase. The target parameters selected were previously identified as important to the underwater phase of the swimming start (Tor, Pease, & Ball, 2014, 2014, 2015). The three possible target parameters were, distance of first kick, breakout distance and maximum depth. The target parameter selected for each subject was the one that deviated furthest from the mean values of the fastest underwater trajectory based on previous research comparing three commonly used trajectories using 15 elite freestyle swimmers (Tor, Pease, & Ball, 2014)(Table 12). Following the pre-test it was determined that Subject 1 and 3 needed to focus on reducing their breakout distance while Subject 2 focused on increasing the distance of their first kick during the intervention phase.

**Table 12 Description and value of the target parameters used to formulate individualized intervention, adapted from (Tor, Pease, & Ball, 2014).**

| Parameter | Description | Mean |
|---|---|---|
| Distance of first kick (m) | Digitised as the distance of the centre of the swimmer's head at the commencement of their first underwater kick upon entry | 6.62 ± 0.68 |
| Breakout Distance (m) | The distance at which the swimmer's head breaks the surface of the water for the first time. | 10.50 ± 1.41 |
| Maximum Depth (m) | The distance the swimmer's head reaches at maximum depth. | -0.92 ± 0.16 |

### 9.3.4 Acquisition Phase

Following pre-testing, subjects completed a four-week intervention period. During this phase subjects completed three training sessions per week, each training session consisted of six maximum effort dive starts on Wetplate (72 dive trials in total). During the four-week intervention phase the feedback schedule was varied (progressively faded) to decrease the subjects reliance on the feedback (Salmoni et al., 1984).

In week one feedback was given following every dive, in week two feedback was decreased from after every dive to every 2nd dive, concluding with a session of no feedback (in session 6). In week three feedback was given after every dive, after every 2nd dive and after the 3rd dive for each session respectively. In week four feedback was only provided after every 3rd dive. For the intervention phase absolute feedback (the total number of trials that receive feedback) was set at 43 trials and relative (the proportion of the total trials having feedback provided) frequency of feedback was 55%.

During each intervention session subjects were given two numbers; the first was the value of the parameter they were focusing on and the second their distance from the parameter's mean. For example, "Your breakout distance was 10.0 m, on the next trial we need you to breakout 0.5 m later." When feedback was given it was provided immediately after the trial was completed, video footage of the trial was also displayed concurrently on a large television screen set-up on the side of the pool. After the swimmer watched the trial once and received the numerical feedback they were asked to identify to the researcher what they needed to alter prior to beginning their next trial eg. "I must focus on getting my breakout 0.5 m later." This was done to reinforce the feedback provided to the swimmer. Subjects were asked to focus on the same target parameter during each training session. To ensure the subjects' normal training did not interfere with the outcomes of the study, the coach and athletes were instructed to keep dives during the acquisition phase to a minimum. All starts performed outside of the study were recorded in a dive diary by each swimmer (Swimmer 1 – 25 dives; Swimmer 2 – 25 dives; Swimmer 3 – 32 dives).

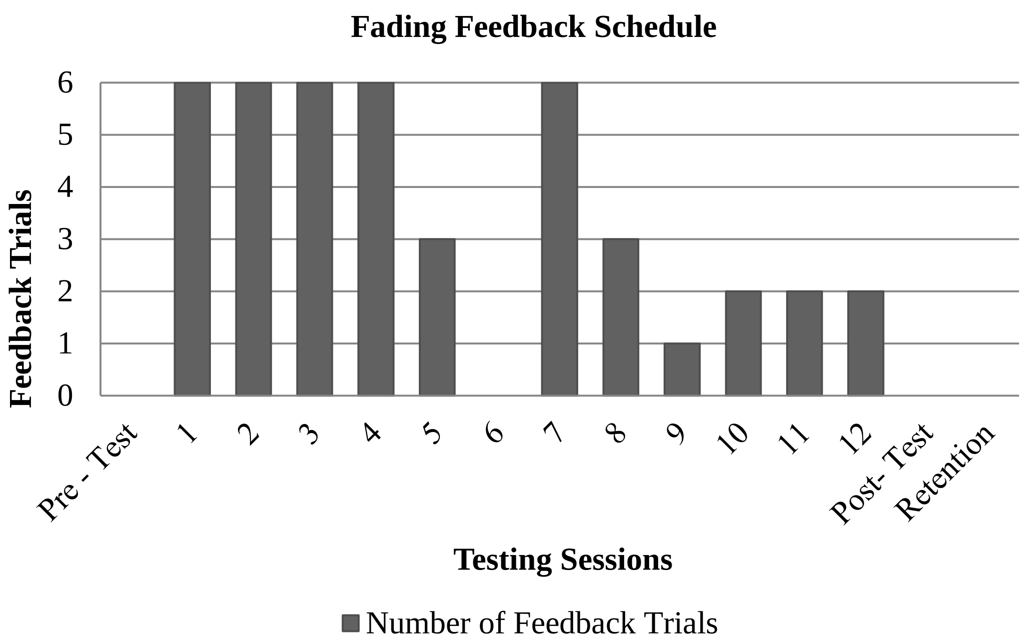



**Figure 14 Schematic diagram of the feedback schedule used.**

### 9.3.5 Post-Intervention and Retention Phase

After the four-week intervention phase a post-test was conducted immediately following the final practice session while the retention test was conducted after two weeks of normal training (no dives performed during this time) to determine if changes in performance were retained. Both tests were conducted in the afternoon (to be consistent with the pre-test) and consisted of six dives to 15 m at maximum effort with two minutes rest between each dive.

### 9.3.6 Statistical Analysis

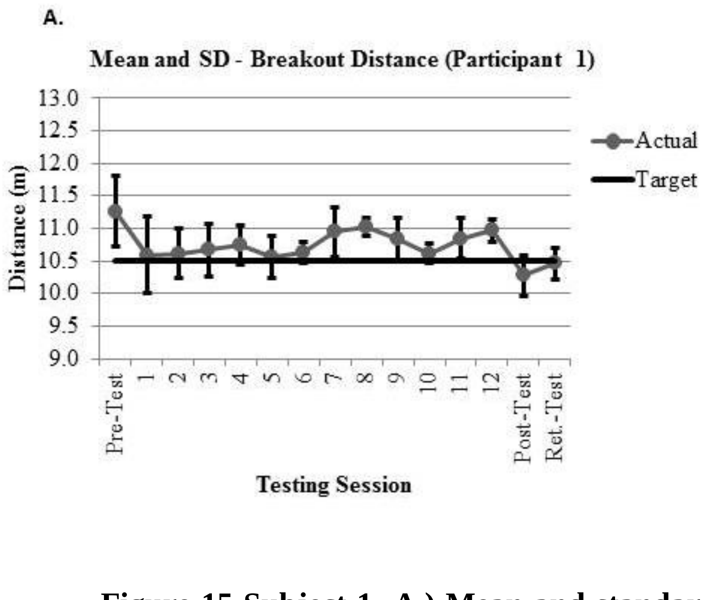
Since each subjects intervention was individualised and their underwater trajectory different, an individual-based analysis was used (see Ball and Best (2012) and Barris et al. (2014)). Descriptive statistics and figures of the selected parameters are presented. Tests for normality were conducted before standard deviations (SD) were used as a measure of variability for each parameter. A lower SD indicated less variability, while a higher SD indicated higher variability in the selected parameter (Tabachnick & Fidell, 1996). It is argued that this statistical approach is important, particularly when examining elite performance (Barris, Farrow, & Davids, 2014; Seifert, Vantorre, Lemaitre et al., 2010).

## 9.4 Results

As an individual approach was used for data analysis, the results are presented by subject (Appendix IV). The target parameter mean and SD for each session (performance curve) with performance (time to 15 m) for the pre-test, post-test and retention test were plotted for each subject (Figures 16-18).

*Subject 1*

Subject 1 was focused on adjusting their breakout distance. Pre-testing revealed a mean breakout distance of 11.26 ± 0.54 m. Following the acquisition period they were able to achieve an average breakout distance of 10.28 ± 0.31 m during the post-test and during the retention test the average breakout distance was 10.46 ± 0.25 m which was closer to the target distance (10.5 m). The performance curve (See Figure 15a) revealed that Subject 1 was able to make quick adjustments during the first few sessions of the intervention before over-correcting then achieving the target parameter during the retention test. The over-correction coincided with when feedback was faded and provided intermittently. Further, Subject 1's underwater trajectory was altered as a result of changing their breakout distance; with less time spent in the descent and ascent portions when compared to the pre-test and the post-test. In turn this led to reduced time spent underwater (3.96 ± 0.29 s: pre-test, 3.22 ± 0.14 s: post-test), a higher average velocity (2.07 ± 0.02 $m{\cdot}s^{-1}$: pre-test, 2.21 ± 0.03 $m{\cdot}s^{-1}$: post-test), a shallower maximum depth (-0.97 ± 0.01 m: pre-test, -0.79 ± 0.03 m: post-test) and a different placement of the first kick (5.29 ± 0.27 m: pre-test, 6.47 ± 0.11 m: post-test) following the glide phase. Even though Subject 1 had a lower average take-off horizontal velocity during the post-test (4.52 ± 0.06 $m{\cdot}s^{-1}$) and retention test (4.36 ± 0.05 $m{\cdot}s^{-1}$), the change in underwater trajectory appeared to allow for the maintenance of a higher underwater velocity which resulted in faster overall start performances. Overall dive performance was fastest for the post-test, performance improvement were not maintained during the retention test, although was still better than the pre-test (See Figure 15b).



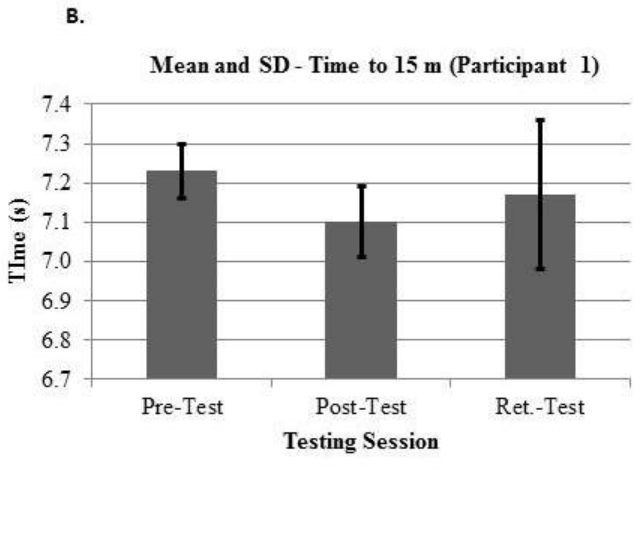




**Figure 15 Subject 1- A.) Mean and standard deviation for breakout distance across all sessions plotted with actual value of target parameter. B.) Mean and standard deviation of performance (Time to 15 m) for pre-test, post-test and retention test.**

*Subject 2*

Subject 2 focused on the distance of their first kick throughout the intervention phase with the target of 6.6 m in mind. Pre-testing revealed a mean distance of first kick was 5.29 ± 0.27 m, following the acquisition phase the post-test distance of first kick was 6.47 ± 0.11 m, while in the retention the average distance was 6.10 ± 0.24 m. The performance curve of Subject 2 (See Figure 16a) displayed consistency in achieving the desired target parameter during all intervention sessions; although this change in technique was not retained during the retention test. During session 1 of the intervention when feedback was provided every trial there were large variances in their performance, after which time Subject 2 seemed to lock in on the desired technique and showed little variance during the subsequent sessions regardless of the feedback schedule. Subject 2 was clearly able to change their underwater trajectory, therefore this did not result in faster overall start performance. Overall dive performance was fastest during the pre-test before increase during the post-test and decreasing slightly during the retention test (See Figure 16b). This lack of performance improvement despite positive change in the target parameter was likely due to performance being variable for other components of the start such as entry angle, distance of maximum depth, breakout distance, breakout time, placement of first kick and time spent underwater parameters throughout each testing session. Further, during the post-test (3.96 ± 0.05 $m \cdot s^{-1}$) and retention-test (3.93 ± 0.05 $m \cdot s^{-1}$) take-off horizontal velocity was much less than during the pre-test (4.36 ± 0.11 $m \cdot s^{-1}$). Consequently, there was a lower average velocity during the 5-7.5 m of the start for both the post-test (1.89 ± 0.05 $m \cdot s^{-1}$) and retention test (1.90 ± 0.04 $m \cdot s^{-1}$) compared to the pre-test (1.97 ± 0.06 $m \cdot s^{-1}$). Therefore, starting the kick later after the glide phase resulted in less deceleration during the later stages of the start particularly between the 7.5-10 m segment (1.65 ± 0.03 $m \cdot s^{-1}$: pre-test, 1.57 ± 0.05 $m \cdot s^{-1}$: post-test, 1.64 ± 0.04 $m \cdot s^{-1}$: retention-test).

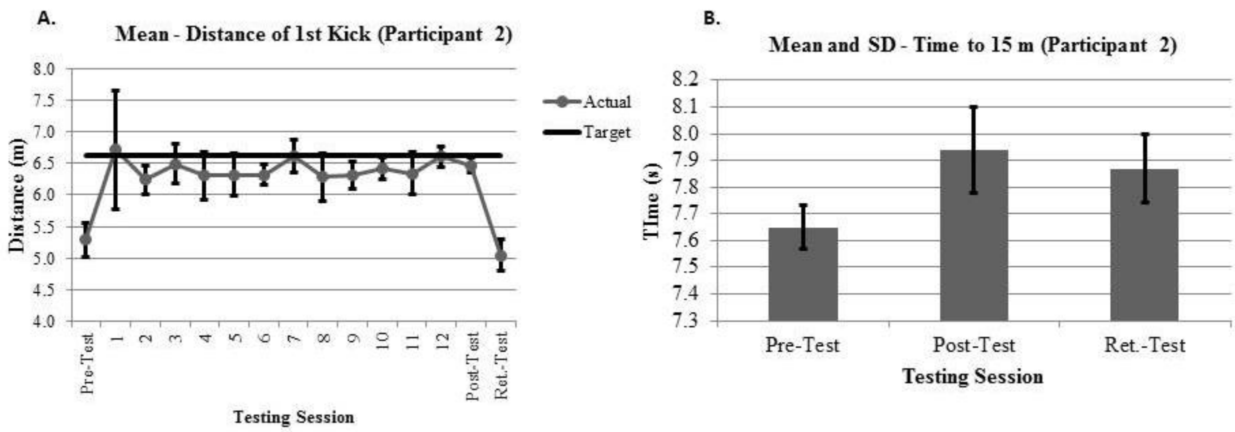



**Figure 16 Subject 2- A.) Mean and standard deviation for distance of first kick across all sessions plotted with actual value of target parameter. B.) Mean and standard deviation of performance (Time to 15 m) for pre-test, post-test and retention test.**

*Subject 3*

Subject 3 focused on decreasing their breakout distance to a target distance of 10.5 m. Pre-testing determined a mean breakout distance of 11.86 ± 0.25 m. Following the acquisition phase they were able to change their mean breakout distance to 10.52 ± 0.10 m during the post-test, this was also closer to the target distance (10.5 m). The performance curve of the target parameter (See Figure 17) showed that Subject 3 was able to make rapid adjustments to their target parameter and remained consistent throughout the intervention phase and retained this skill during the post-test and retention-test. The rapid adjustments made during intervention sessions 1 and 2 occurred while feedback was provided after every trial. During the later stages of the intervention phase Subject 3 was able to consistently achieve the target parameter with little variance, despite the fading feedback schedule. Subject 3's underwater trajectory also changed following the intervention as a result of changing their breakout distance. However, this change in trajectory did not result in improved overall start performance. Time to 15 m was marginally slower for the post-test and retention test when compared to the pre-test (See Figure 17). The main change came during the ascent portion of the underwater phase, which resulted in less time spent underwater (3.62 ± 0.12 s: pre-test, 2.91 ± 0.11 s: post-test, 2.93 ± 0.15 s: retention-test). This may be due to the slower on-block times (0.69 ± 0.02 s: pre-test, 0.71 ± 0.02 s: post-test, 0.75 ± 0.01 s: retention-test) for the post and retention tests as well as lower take-off horizontal velocity (4.79 ± 0.07 $m \cdot s^{-1}$: pre-test, 4.61 ± 0.04 $m \cdot s^{-1}$: post-test, 4.63 ± 0.03 $m \cdot s^{-1}$: retention- test).

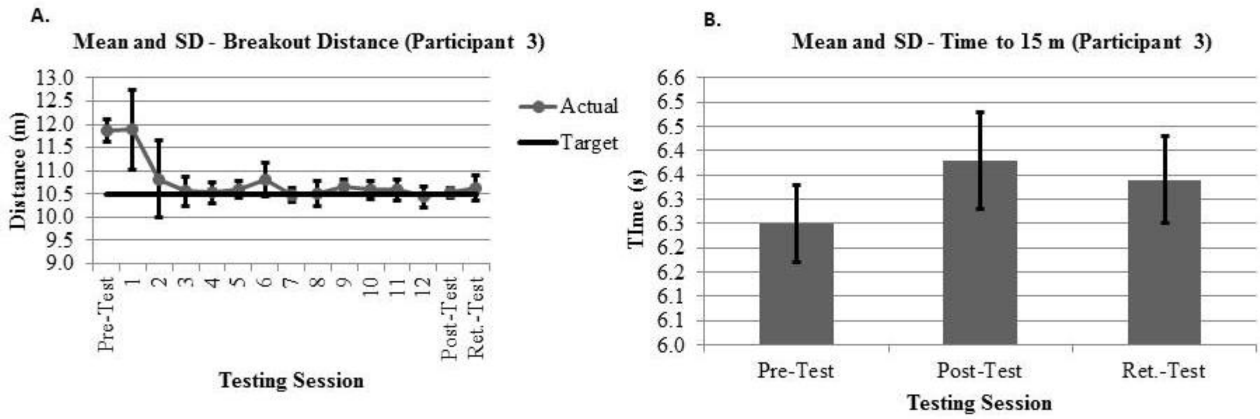



**Figure 17 Subject 3- A.) Mean and standard deviation for breakout distance across all sessions plotted with actual value of target parameter. B.) Mean and standard deviation of performance (Time to 15 m) for pre-test, post-test and retention test**

## 9.5 Discussion

While it has been established that augmented feedback in the form of biomechanical analysis can enhance motor skill learning how the generalised principles of feedback provision derived from laboratory-based studies using unskilled subjects translate to high performance settings involving complex skills is less understood. This study used biomechanical feedback to alter the underwater trajectory of the swimming start of elite performers. Adopting this type of augmented feedback in concert with a faded feedback schedule revealed that each subject was able to change the shape of their underwater trajectory. The subjects were also able to achieve values closer to their target parameter with a high degree of consistency throughout the intervention phase.

Each subject demonstrated a relatively similar pattern of learning during the 1st week of the intervention with rapid changes made to their target parameter. An explanation for this could be that the high levels of feedback during the first three intervention sessions allowed the subjects to be guided to find a more optimal movement pattern. The large SDs shown by all subjects during the 1st week suggests exploration of movement patterns was used relative to the feedback provided after every. During the subsequent weeks of the intervention when feedback was faded Subject's 2 and 3 were consistently able to achieve their target parameter, while Subject 1 demonstrated larger amounts of variance until later in the intervention. These results are generally consistent with other applied feedback studies (Baudry et al., 2006; Thow et al., 2012) and demonstrate that the provision of biomechanical feedback coupled with a fading feedback schedule can be used effectively to make rapid change to a skilled performer's technique.

In a similar study, Thow et al. (2012) found specialised software combined with verbal feedback was effective in improving glide performance during the swimming start, following an eight-week intervention period. However, the precision of the feedback schedule given to each subject was not detailed and performance was not recorded over as many sessions as the current study, making direct comparisons difficult. Consequently, the difference in study design combined with the multiple points (three) each subject was given to focus on during the intervention and the group-based analysis approach may have masked individual variation to learning and skewed the overall results of the study. The design used in the present study accounts for these factors and provides greater insight into individual differences in rates of learning, particularly using an elite athlete population (Ball & Best, 2012).

An individual-based analysis approach was used to investigate the learning effect of a faded feedback schedule over time using an elite athlete population. A faded feedback schedule was selected in an attempt to decrease the subjects' reliance on feedback while still providing a sufficiently feedback rich environment to assist with changes to a complex skill. The rate of change from pre-test to post-test performance of the athletes suggest that the faded feedback schedule was effective in making initial changes to the target parameter. Subjects were able to change their underwater trajectories, hence the scheduling of feedback in this study was effective in the short term; however, retention test performance revealed that only two of the three subjects were able to maintain the changes made to their underwater trajectory. This suggests the number of trials during the intervention may not have been enough for skill learning to be permanent, particularly with a complex movement such as a swimming start. However, given the elite nature of the subjects preparing for major competition, increasing the number of trials or length of design was not feasible for this study. Therefore, future study designs that included more intervention trials and a longer retention period could elicit more permanent changes to performance.

While technique improvements were evident in all subjects, translation to overall start performance was not as conclusive. This is not surprising due to the complex nature of the swimming start. It is logical to accept that there is a period of time required to become comfortable with changes from precise instruction to elicit changes in performance (Phillips et al., 2013). The immediate disruptions to performance were due to the changes in mechanics and the resultant effort required by the performer to implement these changes. Further, the swimming start is made up of a number of different parameters that are all highly related (Lyttle & Benjanuvatra, 2005). Changing one parameter may affect a number of different parameters which could have an adverse effect on start performance. For example, changing the distance of the subject's first kick and breakout distance influenced the maximum depth achieved and time spent underwater during the underwater phase. The current results clearly demonstrate that caution should be taken when using performance time as the only measure of complex skill learning. Instead, when assessing learning using a complex skill multiple parameters should be recorded over time to create a better understanding of technique changes.

Given the study design and accessibility of elite subjects over a long period of time, a limitation of this study was the sample size. Despite these issues, much can be gained from studying populations of elite athletes because their training environment is unique and their experiences are largely varied from the normal population (Sands, McNeal, & Stone, 2005). A unique feature of the current study design was the ability to observe performance of elite athletes for multiple testing sessions over a seven-week period. The use of an individual-based analysis approach also provided valuable insight that is often not provided in such research.

The design and approach used in this study effectively changed the underwater trajectory of three elite swimmer's starts. By observing performance throughout the intervention phase it is clear that biomechanical feedback was used to guide the subjects to their optimal movement patterns during the early stages of the intervention. Furthermore, when feedback was gradually faded subjects were forced to rely on task-intrinsic feedback to achieve their desired movement outcome enhancing (but not guaranteeing) the likelihood of retention. This study demonstrated a clear link between the scheduling of biomechanical feedback and complex skill learning and could be generalised for use by coaches and sport scientists in the applied setting.

# Chapter 10: General Discussion

## Chapter 10.0 General Discussion

It is well established that the swimming start contributes to overall competition performance, particularly in the shorter events (Cossor & Mason, 2001; Lyttle & Benjanuvatra, 2005; Tor, Pease, Ball, et al., 2014). The Omega OSB11 start block was introduced to all international swimming competitions in 2010. This new start block saw the evolution of a start technique known as the kick-start. Research regarding the kick-start technique, particularly involving elite swimmers was scarce, with current studies involving the kick-start technique largely exploring only the first two phases of the start. Given that the swimmer typically spends the longest amount of time in the underwater phase it was pertinent that methods were established to maximise the speed achieved by the swimmer during this section of the start. Therefore, as the underwater phase has been identified as the most decisive factor in determining overall start performance there was a need to conduct research using the kick-start technique, focused particularly on the underwater phase(Guimaraes & Hay, 1985).

This thesis combined performance analysis, biomechanics, hydrodynamics and skill acquisition to accomplish the desired outcomes. The main objective of this thesis was to investigate factors that affect the swimmer during the underwater phase of the swimming start. These factors include the phases prior to entry into the water, the different underwater trajectories utilised and the interaction between drag, speed and depth. To achieve the aims of this research this thesis was separated into four sections; each focussing on a different aspect of the swimming start.

This chapter of the thesis summarises and links together the main findings from each section. Importantly, consideration was also given to the methods used in this thesis with potential avenues for future research discussed. Finally, the practical implications of the current research in this thesis are detailed with limitations of the methods used.

## 10.1 Summary and Practical Applications of Main Findings

### 10.1.1 Section 1 – The Elite Swimming Start (Chapter 3, 4 and 5)

Multiple Studies have previously characterised the grab and track start techniques (Blanksby et al., 2002; Cossor & Mason, 2001; Miller et al., 1984). However, the results from these studies may not relate to the techniques currently being utilised by swimmers during competition with the introduction of the Omega OSB11 block. Further, most of these studies utilised low to moderate numbers of sub-elite subjects (Breed & McElroy, 2000; Kirner, Bock, & Welch, 1989; Seifert, Chollet, & Chatard, 2007; Vantorre, Seifert, Fernandes et al., 2010). The aim of Section 1 was to characterise the elite swimming start and identify key parameters that would affect kick-start performance. Within this section, Chapter 3 established the reliability of the Wetplate Analysis System, Chapter 4 was able to refine the work of previous researchers by using a large sample of elite swimmers to characterise the swimming start using the kick-start technique and an instrumented start block. Further to this, statistical analysis was used in Chapter 5 to identify the key technical parameters that would have the largest effect on start performance.

From the results in Chapter 4 it is clear that elite swimmers spend, on average, the longest amount of time in the underwater phase, 3.69 s which equates to 56% of overall start time. Therefore, it is paramount that coaches and sport scientists develop techniques to emphasise this phase so swimmers can achieve better start performances. Within the underwater phase the trajectory (time underwater in descent, time underwater in ascent), time of first kick, maximum depth and time to 10 m were most important in determining overall start performance. Take-off horizontal velocity was also identified as the most critical above-water parameter for start performance. However, the importance of this parameter is negated if the swimmer does not optimise their speed upon entry into the water by using the correct underwater trajectory to decrease resistance. This finding further emphasised the importance of the underwater phase of the swimming start. In addition, establishing how elite performers start would allow for the design of training programs based on key coaching points derived from scientific research in order to achieve better start performances.

Chapter 4 also aimed to compare start performances between males and females. There are obvious strength and performance differences between male and female swimmers, although these differences had not yet been quantified using the kick-start technique. Most start studies have combined genders or utilised only male subjects. Chapter 4 separated gender and found that there were significant differences between male and female start performances. This is due to males exhibiting greater take-off horizontal velocity, acceleration, force generation off the block and entry velocity. There were also differences in the percentage of time and specific parameters of the underwater phase, males spent longer and travelled further and deeper underwater water, which resulted in males being on average 0.95 s faster to 15 m. Even though males have a clear advantage over females in strength and power, there is some evidence to suggest that females can improve start performance by spending longer underwater. Consequently, due to the differences in start performance and technical parameters, gender was added as a covariate in all subsequent statistical analysis in this thesis.

Differences in technical aspects of the start were also found between freestyle and butterfly. Chapter 4 compared freestyle and butterfly kick-start performance using elite swimmers and it was found that there were no differences during the first two phases of the start. Previously, only a handful of studies by Strojnik et al. (1998) and Whitten (1997) had used the grab start to compare between freestyle and butterfly. These studies found that there were significant differences in the flight phase (Strojnik et al., 1998) and the underwater phases (Whitten, 1997). The difference between strokes in Chapter 4 occurred after the swimmer entered the water, with butterfly swimmers able to travel deeper and longer underwater. However, these differences resulted in no variation in overall start performance. As a result of this finding, butterfly swimmers were excluded from subsequent studies (Chapter 6, 7, 9) to decrease any discrepancies that may have occurred when investigating the underwater phase in more detail.

The second part of this section aimed to identify the main parameters that would affect overall start performance. A combination of factor analysis and multiple regression was used to analyse a large number of retrospective Wetplate dive trials from Australian Olympic and World Championship representatives. A number of difference parameters were shown to contribute to good start performances and were split into above-water (parameters that occurred before the swimmer entered the water) and underwater (parameters that occurred after the swimmer entered the water) groupings. Take-off horizontal velocity has been identified as the most important parameter during the above-water phase. Even though the main aim of this thesis was to investigate the underwater phase of the swimming start the above-water parameters were included in the analyses Chapter 4 and 5. This is because the initial velocity of the glide would depend highly on the preceding actions such as entry velocity following the flight phase. Given this, coupled with the already known differences in above-water parameter when using the kick-start technique it was important to include the first two phases of the start in the analysis. Albeit, as previously mentioned, increasing take-off horizontal velocity while neglecting the underwater phase would negate any advantages in overall start performance as the swimmer may be predisposed to increases in resistive forces. This justified Chapter 5,6,7,8 and 9 placing added emphasis on the underwater phase.

The key parameters of the underwater phase for start performance were time underwater in descent, time underwater in ascent and time to 10 m, extra specific statistical analysis also revealed that time of maximum depth, time of first kick and horizontal distance of maximum depth would significantly affect the underwater phase. These parameters along with time underwater in descent, time underwater in ascent and time to 10 m would affect the trajectory adopted by the swimmer. It has already been identified that the trajectory used by the swimmer during the underwater phase would have implications on the amount of drag acting on the swimmer and in turn the velocity achieved (Houel et al., 2012). Consequently, it was important to identify the factors that affect the underwater trajectory of the swimming start and study these elements in more detail. To an extent the right combination of these parameters is individual. However there is still value in identifying the main parameters that would contribute to start performance using elite swimmers. These main parameters identified using a large population of elite swimmers would provide coaches and sport scientists a guide to improving start performances in the future.

### 10.1.2 Section 2 – Comparing Three Underwater Trajectories (Chapter 6 and 7)

In the swim start literature there has been a discrepancy in the definition of start time (performance), the method of data collection and the start techniques used for analysis. This has made it difficult to compare the results of previous studies to the results within this thesis. In this thesis total start time was defined as the time from the starting signal to when the centre of the swimmer's head reached the 15 m. As already established in Chapter 4 and Chapter 5 there are a number of parameters that combine together to comprise total start time. To conduct detailed analysis of the start, multiple split times were compared in order to isolate particular phases of the start and assess overall performance. By adding this to the experimental design the changes in speed during the underwater phase were able to be more closely investigated. Section 2 (Chapter 6 and 7) utilised some of the findings from Chapter 4 and 5 to compare three underwater trajectories using a comparative study design.

With much debate in the literature about the influences of personal preferences on comparative study designs, further analysis was conducted in Chapter 6 to determine if swimmers always performed best using their preferred technique. Chapter 6 in Section 2 of the thesis found that a comparative study design using elite swimmers was not flawed, as previously thought by Hay (1986). Swimmers were able to readily change their underwater trajectory with little training. Further, there were a number of swimmers who performed faster using a non-preferred technique. This suggests that the study design not only identified each swimmer's fastest underwater trajectory but was also advantageous in allowing swimmers to try a different technique to help optimise their start performances. Practically, this study design could be used to effectively investigate other skill aspects of swimming and should be considered by coaches and sport scientists to determine if swimmers have optimised their technique.

After having identified the importance of the underwater phase, particularly the underwater trajectory in Chapter 4, Chapter 7 compared three underwater trajectories used by elite swimmers during competition. Comparison of three common underwater trajectories (established in Chapter 4) in Chapter 7 found the trajectory which would produce the fastest start performance. Although optimal gliding path following the swimming turn has been examined (Lyttle et al., 1998), Chapter 7 of this thesis was the first to compare underwater trajectories using the kick-start technique with an elite population. It was found that the fastest trajectory is a trade-off between the time spent underwater and the maintenance of velocity generated during the first two phases of the start. Therefore, when coaches and swimmers select their underwater trajectory it must be deep enough to reduce the effect of drag while still not so deep as require excessive amount of vertical travel and hence greater resultant distance. By adopting the correct underwater trajectory the swimmer is able to maintain a higher velocity for longer during the underwater phase.

### 10.1.3 Section 3 – Hydrodynamics and the Underwater Phase (Chapter 8)

This section (Chapter 8) was designed to explore the relationship between drag, speed and depth. These factors have already been shown on multiple occasions to be the main determinants of total drag (Guimaraes & Hay, 1985; Houel et al., 2012; Pereira et al., 2006; Vennell et al., 2006), however these studies did not isolate the contribution of wave drag. When examining the underwater phase it is paramount that the effect of wave drag is accounted for as it is considered the most deleterious type of drag (Rushall, Holt, et al., 1994). A reduction in wave drag is important during the underwater phase of the swimming start, as a reduction in wave drag would translate directly to an improvement in start performance for the same initial conditions of speed and angle of water entry. Hence, Chapter 8 used a novel method involving the use of acoustic sensors to map the surface of the water for the determination of wave drag.

The results from Chapter 8 can be combined with other findings from this thesis and used in a practical sense to make recommendations on the depth swimmers should use during the underwater phase of the swimming start to reduce the amount of wave drag acting on them. For instance, in Chapter 4 it was demonstrated that elite swimmers can maintain underwater velocities of 2.38 $m \cdot s^{-1}$ throughout the underwater phase and at this speed there is an 80% decrease in wave drag when below 0.5 m. Consequently, it is recommended that swimmers should travel deeper than 0.5 m under the surface for as long as possible to reduce the effects of drag, in particular the wave drag component. These findings can also assist to explain how the Dive 2 underwater trajectory in Chapter 7 was significantly faster than Dive 1 and marginally faster than Dive 3.

### 10.1.4 The Ideal Underwater Trajectory

In this thesis the underwater trajectory of the swimming start is defined as the path the swimmer travelled underwater from head entry to breakout. Using the results from Sections 1,2 and 3 a number of theoretical guidelines were able to be established for the ideal underwater trajectory, which could be used to elicit reductions in drag. These guidelines can used by coaches and sport scientist and be specifically applied to elite freestyle swimmers, similar to those tested throughout this thesis. While it can be argued that each swimmer's underwater trajectory is individual and based on a number of individual factors such as underwater kicking ability and anthropometric characteristics; it is still an optimisation between not travelling too deep where there is an advantage of wave drag reduction and minimal distance that would allow for an efficient breakout. Thus, establishing evidence based guidelines is useful for coaches for a more targeted approach to start improvement.

The depth at which the swimmer is travelling during the glide and undulatory kick phase can have a positive effect on reducing hydrodynamic drag, and hence the trajectory adopted by the swimmer is important to reduce deceleration for good start performances. The outcomes of Chapter 4-7 suggest that because the swimmer spends much longer in the underwater phase the trajectory used is paramount to the overall success of start performances. This is due to the fact the swimmer would experience much more resistance travelling through water, than air. Hence any increases in magnitude of the first two phases would be negated immediately upon entry due to increases in deceleration if the swimmer uses an incorrect trajectory. Given this, these recommendations have been able to refine earlier work by Houel et al. (2012) and can now be applied practically using the kick-start technique, which is currently being used by most swimmers in competition. The guidelines are displayed visually in Figure 18 and listed below:

- Hold their glide for 2 seconds prior to the first kick.
- Travel at least 0.5 m below the surface for as long as possible.
- Have a maximum depth of between 0.9 – 1.0 m.
- Start their first kick after the centre of their head reaches 6.5 m from the block.
- Aim to breakout around 10.5 m.

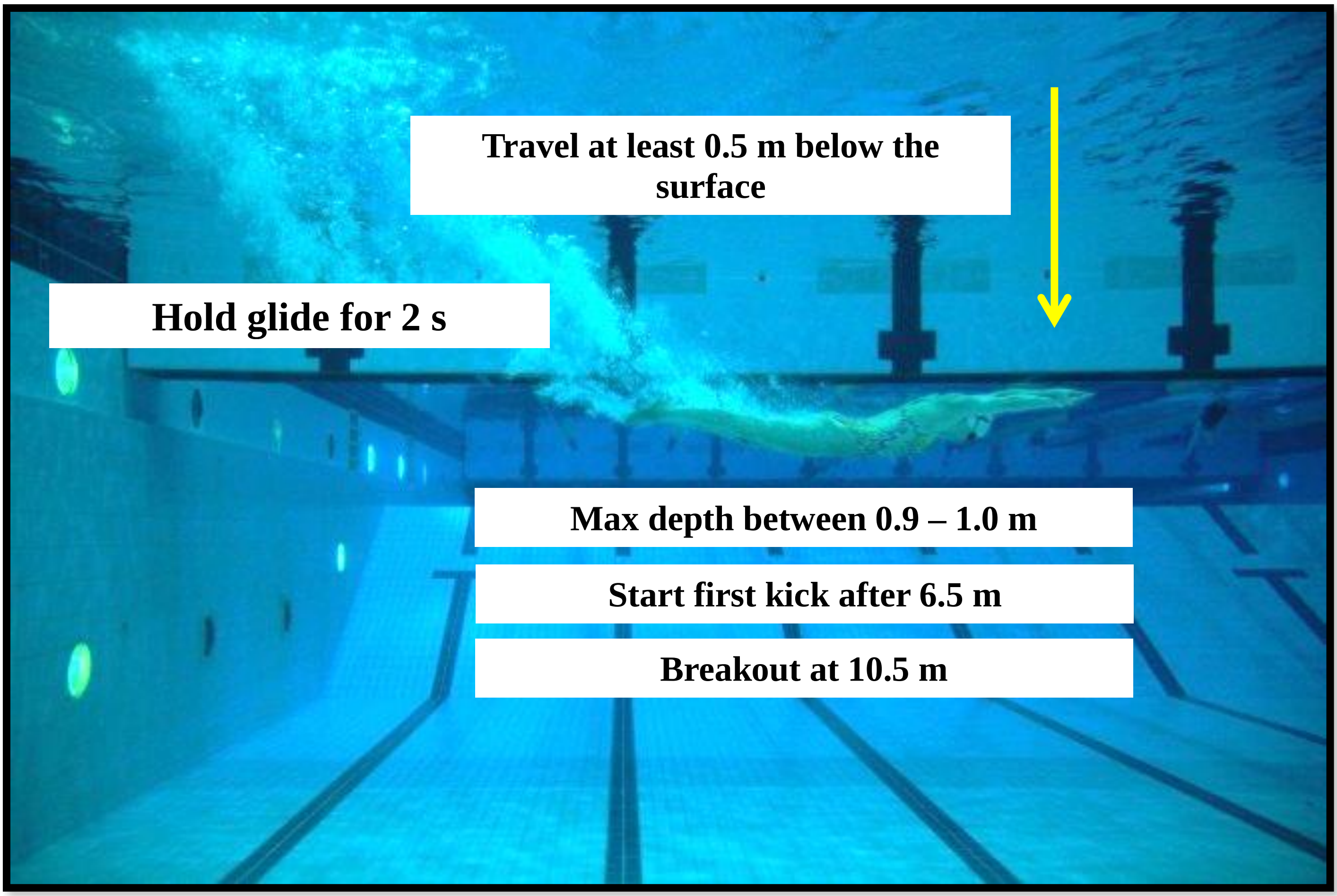



**Figure 16 Theoretical recommendations for the ideal underwater trajectory**

It is understood that actions during the on-block and flight phases would affect the speed achieved during the underwater phase (Lyttle & Benjanuvatra, 2005; Vantorre et al., 2014). The above-water parameters would provide the initial conditions for the underwater phase (speed, angle of entry) but how these parameters are subsequently managed after the swimmer enters the water can differ and rely heavily on the trajectory used in the underwater phase. Consequently, the actions indicated in the guidelines from the ideal underwater trajectory would reduce the amount of resistance acting on the swimmer, leading to the maintenance of a higher velocity during the underwater phase without unnecessary energy loss; ultimately resulting in faster start performances. Minimising the drag experienced by a swimmer during the underwater phase would enable the propulsive efforts in the forward direction to be maximised. In this case it would allow for more speed to be generated as the swimmer commences undulatory kick following the glide phase.

Furthermore, Chapter 4 also found an elite swimmer would enter the water at approximately 6.0 $m.s^{-1}$ then decelerate to approximately 2.38 $m.s^{-1}$. As such, if the swimmer selects the wrong trajectory, depth or kicks at the wrong time they would increase the resistance acting on them and decelerate to a greater extent, negating any increase in take-off horizontal velocity. Initiating a premature action during the glide phase can result in increasing physiological costs as well as unnecessary loss of speed compared to the speed maintained in a passive glide position (Naemi & Sanders, 2008). This further highlights the importance of the underwater phase and choosing the correct trajectory. Combining these results with knowledge of the swimmer's underwater kicking ability and individual anthropometric characteristics in future studies would allow for more individualised approaches to achieving the ideal underwater trajectory.

As has already been stated in Chapter 4, the swimming start is a complex movement comprised of a number of different phases. There are a number of parameters that are closely interlinked and contribute differently to overall start performance. The use of performance analysis in Chapter 4 and 5 the underwater phase was identified as the most important aspect of overall start performance. Within the underwater phase, the trajectory, maximum depth and timing of first kick were also identified as key parameters for performance. Following on from these findings, Chapter 7 was able to determine which trajectory and combination of key parameters would be fastest for performance. Chapter 8 was then able to provide the theoretical basis for the results in Chapter 7 through the use of hydrodynamic analysis. By combining the findings from Section 1, 2 and 3, a multi-disciplinary approach was used to establish theoretical recommendations for the ideal underwater trajectory for the elite sample of swimmers used for the studies in this thesis.

#### 10.1.5 Section 4 – Training the Ideal Underwater Trajectory

The aim of Section 4 was to determine if specific qualitative instruction in the form of biomechanical feedback could be used to change the underwater trajectory of the swimming start in elite swimmers. By using biomechanical feedback and an individual-based analysis approach, the findings from Section 1, 2, and 3 were able to be combined again. Specifically, the values of the ideal underwater trajectory were derived from the findings relating to the fastest trajectory in Chapter 7 and theoretically justified using the findings in Chapter 8. The rationale for this was that previous research surrounding augmented feedback utilised simple laboratory based tasks, which did not relate to the complex tasks often used in sport. Given the established importance of external augmented feedback particularly where intrinsic feedback is low or difficult to interpret, such as swimming (Baudry et al., 2006), it was appropriate to include a final skill acquisition based chapter in this thesis to tie together all of the sections and provide a practical method for the coaches to use in the future to enhance swimming skills.

As a result of the intervention phase in Chapter 9 subjects were able to change their underwater trajectories suggesting the scheduling of feedback in this study was effective in the short term. However once it was removed, some subjects were unable to maintain changes to their trajectories to make performance improvements during the retention test. This implies the feedback used may have been detrimental to performance for two out of three of the subjects in this study, even though their technique had changed. Thus, more trials and a longer retention may be needed in the future for more permanent effects on overall start performance.

Overall, Section 4 (Chapter 9) has demonstrated that swimmers can be taught the ideal underwater trajectory. This is evidence that precise feedback from biomechanical analysis coupled with a fading feedback schedule can be used effectively to make rapid change to a swimmers' technique. Despite not all subjects, showing an improved overall start performance, the approach of biomechanical feedback was still effective in altering elite swimmers' technique. A key point to note from the results of this section is that individuals learn with different styles and at different rates. Subsequently, even though changes were made to each subject's technique, more time may have been needed for the subjects to explore and optimise their movements to elicit permanent changes to performance. In the future, the individual-based approach to skill improvement based on biomechanical feedback could be effective for performance improvement in movements other than the swimming start.

## 10.2 Methodological Implications

### 10.2.1 Novel Methodology

This thesis utilised a number of data collection methods novel to swimming biomechanics. The first was the use of a multi-disciplinary approach to researching the swimming start. The combined biomechanical and performance analysis study design utilised in Section 1 was useful in guiding subsequent research methods within this thesis. The statistical analysis approach used in Chapter 4 and 5 was useful in highlighting critical factors of start performance that were not previously available or traditionally reported using solely competition analysis without the use of specialised equipment such as the Wetplate Analysis System. Furthermore, using performance analysis in the form of statistical analysis alone would not have provided information regarding the underlying mechanisms and process that underpin how the key parameters of the underwater phase affect overall start performance. Hence, more detailed biomechanical analysis was conducted in Sections 2 and 3 to support the findings in Section 1. By using a multi-disciplinary approach key parameters of the underwater phase were able to be identified and explored in detail. The multi-disciplinary approach used in this thesis is not limited to only the swimming start; comprehensive analysis should be done on all skills where elite data is available to provide a more targeted approach to biomechanics servicing.

The second novel technique utilised in this thesis was the separate measurement of wave drag using human swimmers, as opposed to estimating wave drag based on total drag measurements. Chapter 8 used a dynamometer to tow swimmers at various controlled speeds and depths, while acoustic sensors were mounted 0.9 m above the surface of the water to measure wave drag. Towing swimmers through the water in the streamlined position is a common method of measuring passive drag. However, there have been conflicting results reported in previous literature, due to the variances in towing techniques and depth control, making comparison difficult. The towing method used in Chapter 8 utilised minimal equipment in order to ensure the flow around the swimmer was disrupted as little as possible while they travelled through the water. Furthermore, Chapter 8 was able to extend on the earlier work of Vennell et al. (2006), Pease (2010), Pease (2013), Pease and Vennell (2011) who suspended mannequins face up in a flume. This thesis was the first to directly approximate wave drag using human swimmers in the face-down position using acoustic sensors and the LWC method. Toussaint (2006) and Lyttle et al. (1998) have previously measured wave drag using human swimmers, however their methods were based on estimations of total drag. The use of 3D laser scans, acoustic sensors and the LWC method of calculating wave drag in this thesis demonstrated an effective method of wave drag estimation. This method can now be used in the future to further extend on the findings from Chapter 8.

### 10.2.2 Individual vs Group-Based Analysis

It is important to understand the difference between individual and group-based analysis as choosing the suitable research approach should be based on the available resources and study outcomes (Kinugasa, 2013). This thesis highlighted the importance of considering both approaches or using a combination of both. Chapter 4, 5, 7 and 8 used a group-based analysis, while Chapter 3, 6 and 9 utilised an individual approach. Traditionally swimming start biomechanics studies used a group-based approach and looked for significant statistical differences to answer research problems (Blanksby et al., 2002; Burkett et al., 2010; Cossor & Mason, 2001; Honda et al., 2010; Houel et al., 2012; Lyttle, Blanksby, et al., 1999; Thow et al., 2012). However, particularly when working with elite performers, the group-based approach may not be appropriate for all situations (Kinugasa, 2013).

There are a number of issues associated with choosing the correct analysis technique (Ball & Best, 2012). Firstly, group-based analysis can mask significant performance factors. For example, the group-based performance analysis study design used in Chapter 5 did not account for each individual's strengths and weaknesses. The results were useful in characterising elite start performance, although the results may not apply to all individuals or swimmers who are below the elite standard. Secondly, individual-based analysis can provide important information to coaches in regards to the athlete's movement pattern. The individual approach used in Chapter 9 was useful in identifying one aspect of each swimmer's underwater trajectory for a more targeted approach to performance improvement. Finally, some researchers believe, that most clinical approaches are individual, particularly in clinical biomechanics. In an elite sport setting Ball and Best (2012) found that individual analysis was able to uncover significant individual specific results that were not identified using group-based analysis of the golf swing. Hence, group-based analysis for all circumstances may not be appropriate.

This thesis provided strong evidence supporting the use of both group and individual based analysis. In this thesis a group-based approach was used to identify key performance indicators before an individual-approach was used to conduct more specific analysis on technique changes with elite athletes. For example, in Chapter 4 and 5 a group-based approach was used to conduct performance analysis on a large number of elite start performances. By using this approach, standards established and insight into elite performance was critically analysed for the future benefit of coaches. Group-based analysis was also used in Chapter 7 to generalise results for a larger population and Chapter 8 to encompass a larger range of body types. Adopting this approach for these particular studies was valid to meet the desired outcomes of the studies. Individual-based analysis was used in Chapter 6 to highlight the use of a comparative study design and to demonstrate that elite athletes are able to readily change their technique with little practice. Individual-based analysis was also used in Chapter 9 to account for the individual variances in start performance (i.e. different swimmers would be deficient in different areas), especially at the elite level. Further, due to low numbers an individual approach was used for analysis and determination of each subject's intervention. Grouping results in this situation may have returned incorrect findings.

Overall, there have been arguments for and against using both of these analysis methods in the past. A combination of group and individual based analysis, like the approaches used in this thesis was affective in extracting all information and would assist to enhance coaches and sport scientists' understanding of the practical issues in applied sport science.

**10.3 Limitations**

Throughout this thesis there were a number of limitations associated with the study methods used. The first surrounds the towing methods used to measure drag. Given the towing methods used, the control of postural changes and smaller depth increments were difficult to achieve. Even though Chapter 8 was able to expand on previous research there was some variance in drag values for the below surface conditions between 1.6 $m \cdot s^{-1}$ and 1.9 $m \cdot s^{-1}$, these findings differed slightly from that of Vennell et al. (2006), with the current study exhibiting slight higher values. This difference may be partly due to the use of human swimmers in this thesis rather than mannequins. However it is important to note these changes would naturally occur during free-swimming and gliding and were hard to control for when using minimal equipment. A limitation of using human subjects is there are natural positional changes in the horizontal and vertical plane which can occur when towing the swimmers through the water, particularly at lower speeds. In fact, Bixler et al. (2007) found an 18% difference (increase) in drag for human swimmers compared to mannequins due to swimmers unable to consistently hold an optimal streamlined position throughout testing. These subtle positional changes found in the Bixler et al. (2007) study and this thesis would change the angle of attack and consequently alter the value of frontal area. Pease and Vennell (2011) found that a slight positive angle of attack would cause a greater contribution of wave drag to total drag due to an earlier separation of flow which disturbs a greater water mass, while a negative angle saw a lower contribution of wave drag to total drag. Hence, slight changes in the angle of attack while the swimmer was in the glide position may have resulted in an over or under estimation of drag, particularly at lower speeds. However, the effects of depth on wave and total drag far outweighs those of changing the angle of attack (Pease, 2010). Regardless of these limitations it remains an advantage of using human swimmers as the results are more ecologically valid and generalisable to human swimming.

Another limitation of the drag measurements used in this thesis was the maximum speeds used for towing. The fastest speed selected for towing in Chapter 8 was 2.5 $m \cdot s^{-1}$. This speed is slightly slower than similar towing studies (Lyttle & Blanksby, 2000; Lyttle, Blanksby, et al., 1999; Sheehan & Laughrin, 1992), however it was the fastest speed that could be accurately achieved by the dynamometer used. It could be argued that the findings from Chapter 8 cannot be applied to the swimming start as the speeds used during testing were far slower than those experienced by the swimmer upon entry into the water. Nevertheless, once the swimmer enters the water, Chapter 4 found that the swimmer would rapidly slow down to an average speed of 2.38 $m \cdot s^{-1}$. This deceleration typically occurs very rapidly and does not allow for the swimmer to make any adjustments to reduce the amount of deceleration occurring until they adopt a streamline position and slow to approximately 2.38 $m \cdot s^{-1}$ during the glide phase. Hence, the findings from this thesis should still be able to be applied to the underwater phase of the swimming start.

Finally, prior to testing in Chapter 6,7, and 9 athlete training loads around testing times were considered a potential limitation due to increased fatigue levels. These chapters used a testing period spanning multiple sessions and required subjects to perform at maximal effort. It would have been ideal to keep in-water training and gym sessions to a minimal during this time to reduce effects of fatigue on these tasks, or perhaps (and more importantly) variations in fatigue between sessions. This scenario however, is extremely unlikely within an elite population given the year round training that is performed and might in itself influence results with detraining effects. To minimise the effect of athlete training commitments testing days were specifically chosen for recovery days where the swimmers had lighter loads and did not train prior to testing in Chapter 6 and 7. As the intervention and testing period was much longer for Chapter 9, outside influences on testing performance were harder to control. The coach of each athlete was requested to keep dives to a minimum during the testing period and a diary was kept throughout to monitor dives completed during training outside of the intervention phase. Testing was also chosen for a period where training load was maintained and not increased. While training loads are often difficult to control, particularly when using elite athletes, the findings in this thesis were minimally affected by the strategies employed. Furthermore, the insights gained from utilising elite athletes for research studies such as those in this thesis far outweighs decreasing the calibre of athlete due to training commitments.

## 10.4 Future Directions

This thesis used novel approaches to make advances in swimming research. However, there are a number of aspects which stem from the current research that should be considered to further extend the work in this thesis. Firstly, future studies should compare swimmers of differing skill level and gender to expand on the findings from the current research. It has been well established previously that there are differences in novice and elite performers in any skill.

As this thesis incorporated mainly experienced athletes the findings may not necessarily apply to novice or developing athletes. In particular, the mean values from Chapters 4 and 5 were based on a large cohort of elite swimmers. The characteristics of the start established in these chapters may not generalise to less experienced swimmers due to skill, strength and power features. Hence, the same statistical methods should be utilised with novice and sub-elite athletes. In doing so, different standards could be established and potentially tracked over time for insight into the development of start performance from sub-elite to elite performers.

Secondly, there are obvious merits to conducting large-scale, group-based analysis as demonstrated in Chapter 4, 5, 6 and 7. These include establishing guidelines for elite performance for coaches, increasing statistical power and increasing generalisability. However, as swimming performance at the elite level is separated by small margins future biomechanical research should focus on becoming more individualised. Individual differences at the elite level were highlighted in Chapter 9 when each swimmer was given a target parameter based on their dive trajectories during the pre-test. A proposed future individual approach would involve utilising the methodology and overall design of this thesis. For example, the use of performance analysis and statistical analysis could first be used to pin-point key parameters of a particular movement, similar to Chapter 5 before a tailored biomechanical intervention can be applied. This would account for individual strengths and weaknesses, anthropometry and range of motion. It would also provide an extension on the methods in this thesis and could have a great impact on performance at the elite level by promoting a more targeted approach to skill improvement.

Despite the previously mentioned limitations of the drag measurements used; with advancements in depth control the findings in this thesis can be expanded further. Specifically, a combination of the flume methods using in Vennell et al. (2006) and the methods used in Chapter 8 should allow for smaller increments in depth while still using human subjects. Using this combination of techniques, could potentially allow for more detailed drag curves and individualised predictions based on the swimmers height, frontal cross-sectional area and underwater kick ability. Moreover, as identified in Pease and Vennell (2011) more detailed information regarding the flow around the body can be collected through analysis of the curvature of the swimmer's body. To further extend and tailor the findings from this thesis, individual curvature analysis from 3D laser scans should be included during drag testing. Following this, in concert with more detailed drag curves an approach to mathematically model each swimmer's ideal underwater trajectory may be possible. Similar individualised advancements can be achieved using computational fluid dynamics, however this method can be time consuming and costly. A mathematical model might provide coaches and sport scientists with a much more efficient and practical way of improving the swimming start by individualising the findings from Chapter 8 and recommendations for the ideal underwater trajectory.

The final recommendation for future research is to use the methods established in this thesis to investigate the underwater phase of backstroke and breaststroke. This has previously been done in breaststroke (McCabe et al., 2012) and (de Jesus, de Jesus, Morais et al., 2014). However, the effects of drag during these starts have not been investigated in the same amount of detail as this thesis. While the same theoretical principles can to an extent, be applied to all starts there may be slight variances in breaststroke due to the difference in underwater regulations and backstroke as a dive action is not used for entry into the water and the swimmer is also in the supine position. Breaststroke and backstroke start performances would be able to benefit from the research methods utilised in this thesis.

# Chapter 11: Overall Conclusion

## Chapter 11.0 Overall Conclusion

The primary aim of this thesis was to determine the main factors that affect the underwater phase and how these aspects would affect overall start performance. This was the central focus of the thesis because previous research had identified the underwater phase as the most decisive factor in determining efficient start performances (Cossor & Mason, 2001). However, past research primarily utilised older starting techniques which have been phased out with the introduction of the Omega OSB11 starting block. Subsequently, elite kick-starts were first characterised in order to establish the contribution of each sub-phase to the overall start, to evaluate differences between male and female and compare between butterfly and freestyle. This was one of the few studies to characterise the kick-start technique using a large cohort of elite swimmers and confirmed that during the start an elite swimmer would spend the longest amount of time in the underwater phase. This is also when the swimmer is travelling at their fastest through the water, emphasising the importance of improving this phase for better start performances.

Using the same elite sample this thesis identified a number of key parameters within the underwater phase that would impact on overall start performance. These were time underwater in descent, time underwater in ascent and time to 10 m. Further analysis also revealed maximum depth and time of first kick as additional factors that would affect the underwater phase of the swimming start. In this study the above-water phases of the start were also examined and it was found that take-off horizontal velocity was paramount. However, the effect of this parameter would be negated if the swimmer does not optimise the underwater phase, due to the increased amount of resistance that may act on them causing deceleration. Given this, coupled with the underwater phase being the longest, a larger emphasis was placed on the factors that affect the final phase of the start in the ensuing chapters.

As the underwater trajectory adopted by elite swimmers during the swimming start was ascertained as important to overall start performance, a subsequent comparative design was utilised to determine which common underwater trajectory is the fastest. Three common underwater trajectories were tested and it was found that the fastest trajectory was a trade-off between a depth that was deep enough to reduce the effect of drag and shallow enough so that the swimmer was still travelling predominantly in the desired horizontal direction. To provide a theoretical basis for these findings this thesis also explored the relationship between drag, depth and speed. The main resistance that acts to slow the swimmer down during the underwater phase is drag and hence determining ways to reduce this would allow for a higher velocity to be maintained for longer. This thesis found that swimmers should travel at least 0.5 m below the surface of the water to reduce the amount of resistance acting on them. Specifically, if a swimmer travels below the surface at 0.5 m during the underwater phase they would experience approximately 80% less wave drag compared to travelling at the surface.

The secondary aim of the thesis was to use biomechanical feedback to train swimmers to an individualised underwater trajectory based on the findings from previous chapters within the thesis. Combining the key findings from the entire thesis chapters, theoretical recommendations were established for the ideal underwater trajectory swimmers should adopt to reduce the amount of drag acting on them. These recommendations were then applied and tested in the final study of this thesis. The final chapter was a skill acquisition study that utilised a complex sport specific skill (the swimming start), biomechanical feedback and a fading feedback schedule to track elite performance over time. The outcomes from the individual analysis conducted were evidence that biomechanical feedback and a fading feedback schedule can be used to alter the underwater trajectory of elite swimming start. Therefore, the main factors identified in this thesis can be altered by the swimmer and consequently can be easily applied by coaches and sport scientists to improve start performance.

This thesis has highlighted the importance of the underwater phase to efficient kick-start performance in elite swimmers. A multidisciplinary approach was used to achieve the outcomes of this thesis. Further, the use of group-based and individual analysis of elite swimmers established a novel approach to investigating the swimming start. While the recommendations stated in this thesis specifically apply to the population of elite athletes sampled, the findings would contribute to the development of evidence-based practice for sport scientists and coaches. The practical implications of this research would also allow sport scientists to provide specific coaching cues surrounding the key parameters for better start performances.

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## Appendix I: Detailed Description of Wetplate Parameters

### Detailed description of the above – water parameters measured by the Wetplate Analysis System

| Parameter | Description |
|---|---|
| Entry distance (m) | The horizontal distance from the start wall to head entry, obtained through digitisation of the above water Wetplate camera image. |
| Time on-block (s) | The time taken for the swimmer to leave the block following the starting signal, this was indicated by zero force exerted by the feet on the blocks. |
| Take-off horizontal velocity ($m \cdot s^{-1}$) | The change in horizontal displacement when the swimmer is leaving the block. The horizontal velocity is derived from the integral of the horizontal force exerted by the swimmer against the starting block during the period from the starting signal until the feet leave the block as measured in body weight and multiplied by the gravitational constant. |
| Take-off vertical velocity ($m \cdot s^{-1}$) | The change in vertical displacement when the swimmer is leaving the block. The vertical velocity is derived from the integral of the vertical force exerted by the swimmer against the starting block from the starting signal until the feet leave the block as measured in body weight minus one body weight and multiplied by the gravitational constant. |
| Time in the air (s) | The time from when the swimmer leaves the block to when the swimmer's head first enters the water (flight phase). |
| Average horizontal acceleration ($m \cdot s^{-2}$) | The horizontal velocity at which the swimmer's CoG leaves the blocks divided by the time the swimmer spent on the block from the starting signal until the swimmer's feet cease to be in contact with the block. Horizontal velocity derived as the integral of horizontal force on the block. |
| Centre of mass angle of entry (degrees) | The angle relative to the horizontal; at which the swimmer's centre of mass is travelling at the point of take-off from the block. This was calculated from the horizontal and vertical components of the centre of mass velocity derived by integrating the respective accelerations calculated from the force data. |
| Dive angle (degrees) | The angle at which the swimmer's centre of mass is relative to the block during take-off. Derived from the horizontal and vertical velocities of the swimmer at the instant the feet leave the block. A downward direction from the horizontal is defined as a negative angle. |
| Entry velocity ($m \cdot s^{-1}$) | The horizontal velocity which the swimmer travels through the air during the flight phase before entry into the water. The calculation is based purely upon simple projectile motion of the CoG acting under the gravitational force together with the location of the swimmer's CoG above the water at the instant of leaving the block together with both the horizontal and vertical velocities of the swimmer's CoG at that point in time. |
| Entry hole diameter (m) | The size of the hole created by the swimmer as they enter the water. Obtained by digitizing the extreme points of the swimmer breaking the water surface during the entire entry phase between the time of hand entry until feet entry (near and far from the blocks). |
| Head entry time (s) | The time point when the head first enters the water after the start. |
| Entry hole distance (m) | The distance from the block as the swimmer enters the water. |

| | |
|---|---|
| Peak footplate force (BW) | The maximum peak value on the footplate force profile experienced at right angles to the foot plate surface by the rear foot during the on block phase of the start with the force normalized to the starter's body weight. |
| Peak grab force (BW) | The maximum force produced by the hands during take-off from the block, normalised to the swimmer's body weight. |
| Peak horizontal force (BW) | The maximum force produced in the horizontal direction by the swimmer during take-off from the block (not including the kick-plate), normalised to the swimmer's body weight. |
| Peak vertical force (BW) | The maximum force produced in the vertical direction by the swimmer during take-off from the block (not including the kick-plate), normalised to the swimmer's body weight. |
| Peak power per kilogram ($w \cdot kg^{-1}$) | The maximal power relative to the swimmer's body weight produced while they are on the block. The power curve profile is calculated as the product of the instantaneous horizontal force exerted by the swimmer and the instantaneous horizontal velocity attained by the swimmer during the on-block phase of the start. |
| Mass of swimmer (kg) | Weight of the swimmer, measured in Newtons from the force plate before being converted into kilograms. The mass of the swimmer is obtained while the swimmer stands stationary on the starting block while the vertical force is captured and averaged over a three second time interval. |

**Detailed description of the underwater parameters measured by the Wetplate Analysis System.**

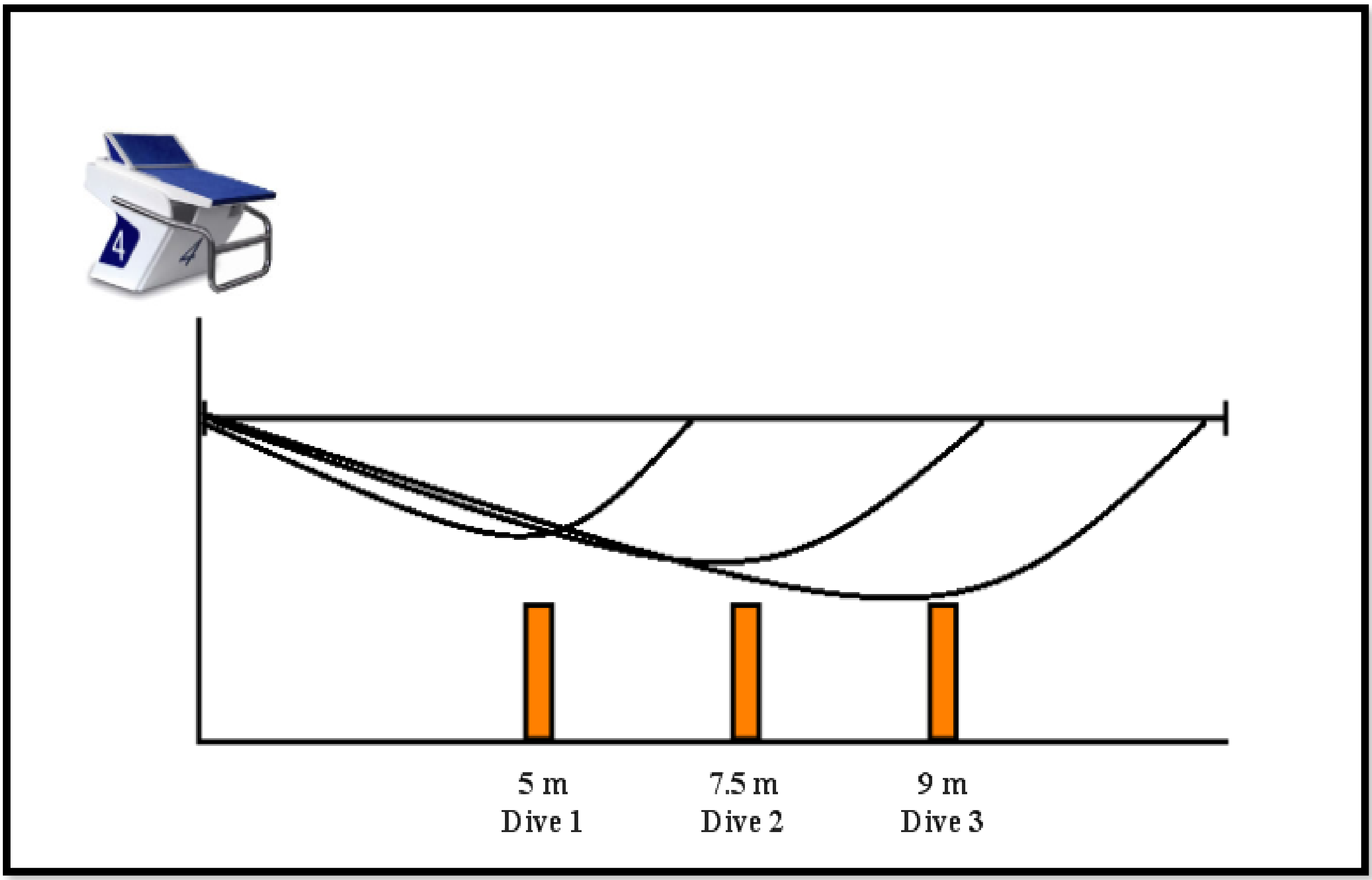
| Parameter | Description |
|---|---|
| 5 m, 7.5 m, 10 m, 15 m split times (s) | The time taken from the starting signal for the centre of the swimmer's head to pass through a line drawn on the image obtained by each of the Swim Trak cameras. |
| Average velocity ($m \cdot s^{-1}$) (0-5 m, 5-7.5 m, 7.5-10 m, 10-15 m) | The segmental average velocity calculated using the formula distance over time (when the centre of the swimmer's head passed each respective time point). |
| Max depth (m) | Digitised at the point where the apex of the head is at the deepest point upon entry into the water prior to ascent. |
| Time of full submersion (s) | The time when the swimmer's body is fully submerged underwater water. |
| Time after entry of first kick (s) | The time point after entry when the first kick is initiated, this is defined as the position of the head at the end of the first down beat during undulatory kick. |
| Time of first kick (s) | The time at which the first kick is initiated by the swimmer has been complete. |
| Distance of first kick (m) | Digitised as the distance of the centre of the swimmer's head at the commencement of their first underwater kick upon entry. |
| Horizontal distance of max depth (m) | The distance from the block at maximum depth (based on the swimmer's head). |
| Max depth of head (m) | The vertical distance below the surface of the water that the swimmer's head reaches at maximum depth. |
| Time at max depth (s) | The time the swimmer's head reaches maximum depth. |
| Time underwater in descent (s) | The time taken for the swimmer's head to reach maximum depth after entry into the water. |
| Time underwater in ascent (s) | The time taken from the swimmer to rise from maximum depth to breakout. |
| Total time underwater (s) | The total time spent underwater from entry to breakout. |
| Breakout distance (m) | The distance at which the swimmer's head breaks the surface of the water for the first time. |
| Breakout time (s) | The time at which the swimmer's head breaks the surface of the water for the first time. |
| Underwater velocity ($m \cdot s^{-1}$) | The average speed the swimmer is travelling during the underwater phase of the dive. Calculated by dividing the underwater horizontal distance travelled by the time spent under the water. |

## Appendix II: Chapter 6 and Chapter 7 Descriptive Statistics

**Mean and standard deviation of selected parameters for each dive condition**

| Parameter | Preferred | Dive 1 | Dive 2 | Dive 3 |
|---|---|---|---|---|
| **Reaction Time (s)** | 0.71 ± 0.04 | 0.71± 0.04 | 0.72 ± 0.04 | 0.72 ± 0.04 |
| **Time in the Air (s)** | 0.35 ± 0.05 | 0.34 ± 0.05 | 0.34 ± 0.05 | 0.35 ± 0.04 |
| **Dive Angle (º)** | -11.2 ± 4.2 | -11.7 ± 3.9 | -11.6 ± 4.0 | -11.4 ± 3.9 |
| **Entry Distance (m)** | 2.96 ± 0.16 | 2.94 ± 0.15 | 2.96 ± 0.16 | 2.96 ± 0.13 |
| **Time Head Enters (s)** | 1.05 ± 0.06 | 1.06 ± 0.06 | 1.06 ± 0.06 | 1.06 ± 0.06 |
| **Entry Velocity ($m.s^{-1}$)** | 6.82 ± 0.13 | 6.81 ± 0.14 | 6.80 ± 0.14 | 6.80 ± 0.13 |
| **Peak Power per Kilogram (w/kg)** | 62.31 ± 7.48 | 60.46 ± 6.73 | 61.41 ± 6.62 | 60.91 ± 6.50 |
| **Take-off Horizontal Velocity ($m.s^{-1}$)** | 4.68 ± 0.24 | 4.65 ± 0.24 | 4.66 ± 0.23 | 4.65 ± 0.23 |
| **Distance at Max Depth (m)** | 5.86 ± 0.79 | 5.03 ± 0.58 | 5.75 ± 0.69 | 6.32 ± 1.21 |
| **Max Depth (m)** | -0.98 ± 0.17 | -0.74 ± 0.14 | -0.92 ± 0.16 | -1.03 ± 0.18 |
| **Time at Max Depth (s)** | 1.78 ± 0.23 | 1.53 ± 0.18 | 1.75 ± 0.22 | 1.98 ± 0.46 |
| **Total Underwater Time (s)** | 3.80 ± 0.70 | 1.88 ± 0.55 | 3.07 ± 0.67 | 4.16 ± 0.57 |
| **Tine in UW Descent (s)** | 0.73 ± 0.25 | 0.47 ± 0.18 | 0.69 ± 0.22 | 0.91 ± 0.45 |
| **Time in UW Ascent (s)** | 3.07 ± 0.64 | 1.41 ± 0.42 | 2.39 ± 0.54 | 3.24 ± 0.58 |
| **Breakout Distance (m)** | 11.91 ± 1.52 | 8.11 ± 1.20 | 10.50 ± 1.41 | 12.43 ± 1.14 |
| **Breakout Time (s)** | 4.85 ± 0.69 | 2.94 ± 0.55 | 4.13 ± 0.68 | 5.22 ± 0.58 |
| **Underwater Velocity* ($m.s^{-1}$)** | 2.37 ± 0.13 | 2.80 ± 0.22 | 2.48 ± 0.17 | 2.29 ± 0.16 |
| **Depth of first kick (m)** | -0.98 ± 0.20 | -0.50 ± 0.24 | -0.89 ± 0.18 | -1.04 ± 0.17 |
| **Distance of first kick (m)** | 6.54 ± 0.68 | 6.16 ± 0.57 | 6.62 ± 0.68 | 6.65 ± 0.69 |
| **Time of First Kick (s)** | 2.04 ± 0.23 | 1.96 ± 0.19 | 2.08 ± 0.24 | 2.09 ± 0.24 |
| **Time to 5 m (s)** | 1.52 ± 0.09 | 1.54 ± 0.09 | 1.53 ± 0.08 | 1.53 ± 0.09 |
| **Avg. Vel. 0-5 m ($m.s^{-1}$)** | 3.30 ± 0.19 | 3.26 ± 0.19 | 3.27 ± 0.17 | 3.27 ± 0.18 |
| **Time to 7.5 m (s)** | 2.47 ± 0.17 | 2.59 ± 0.18 | 2.50 ± 0.16 | 2.48 ± 0.17 |
| **Avg. Vel. 5 -7.5 m ($m.s^{-1}$)** | 2.66 ± 0.24 | 2.41 ± 0.24 | 2.60 ± 0.23 | 2.67 ± 0.25 |
| **Time to 10 m (s)** | 3.76 ± 0.28 | 3.91 ± 0.29 | 3.82 ± 0.26 | 3.79 ± 0.28 |
| **Avg. Vel. 7.5 -10 m ($m.s^{-1}$)** | 1.95 ± 0.18 | 1.91 ± 0.17 | 1.92 ± 0.16 | 1.92 ± 0.18 |
| **Time to 15 m (s)** | 6.48 ± 0.39 | 6.62 ± 0.40 | 6.54 ± 0.37 | 6.56 ± 0.42 |
| **Avg. Vel. 10 - 15 m ($m.s^{-1}$)** | 1.84 ± 0.09 | 1.85 ± 0.10 | 1.84 ± 0.09 | 1.81 ± 0.11 |

*Calculated as (breakout distance – entry time)/total underwater time




**Visual diagram of prescribed underwater trajectories**

## Appendix III: Chapter 8 Descriptive Statistic Tables

### Total drag descriptive statistics

| Towing Condition | Mean ± Standard Deviation |
|---|---|
| 1.6 $m.s^{-1}$ at the Surface | 62.7 ± 8.27 |
| 1.9 $m.s^{-1}$ at the Surface | 92.13 ± 2.42 |
| 2.0 $m.s^{-1}$ at the Surface | 102.88 ± 9.41 |
| 2.5 $m.s^{-1}$ at the Surface | 184.61 ± 18.88 |
| 1.6 $m.s^{-1}$ at 0.5 m | 61.51 ± 9.26 |
| 1.9 $m.s^{-1}$ at 0.5 m | 84.45 ± 99.43 |
| 2.0 $m.s^{-1}$ at 0.5 m | 94.46 ± 11.35 |
| 2.5 $m.s^{-1}$ at 0.5 m | 148.13 ± 255.65 |
| 1.6 $m.s^{-1}$ at 1.0 m | 60.88 ± 8.21 |
| 1.9 $m.s^{-1}$ at 1.0 m | 81.35 ± 10.12 |
| 2.0 $m.s^{-1}$ at 1.0 m | 90.49 ± 12.51 |
| 2.5 $m.s^{-1}$ at 1.0 m | 140.77 ± 15.49 |

### Total wave drag descriptive statistics

| Towing Condition | Mean ± Standard Deviation |
|---|---|
| 1.6 $m.s^{-1}$ at the Surface | 7.27 ± 3.25 |
| 1.9 $m.s^{-1}$ at the Surface | 25.20 ± 7.42 |
| 2.0 $m.s^{-1}$ at the Surface | 37.36 ± 12.51 |
| 2.5 $m.s^{-1}$ at the Surface | 78.82 ± 13.92 |
| 1.6 $m.s^{-1}$ at 0.5 m | 1.63 ± 2.53 |
| 1.9 $m.s^{-1}$ at 0.5 m | 5.06 ± 3.61 |
| 2.0 $m.s^{-1}$ at 0.5 m | 7.16 ± 3.76 |
| 2.5 $m.s^{-1}$ at 0.5 m | 19.68 ± 10.58 |
| 1.6 $m.s^{-1}$ at 1.0 m | 0.33 ± 0.21 |
| 1.9 $m.s^{-1}$ at 1.0 m | 0.81 ± 0.40 |
| 2.0 $m.s^{-1}$ at 1.0 m | 1.17 ± 0.65 |
| 2.5 $m.s^{-1}$ at 1.0 m | 3.90 ± 1.76 |

### Froude Number for each towing condition

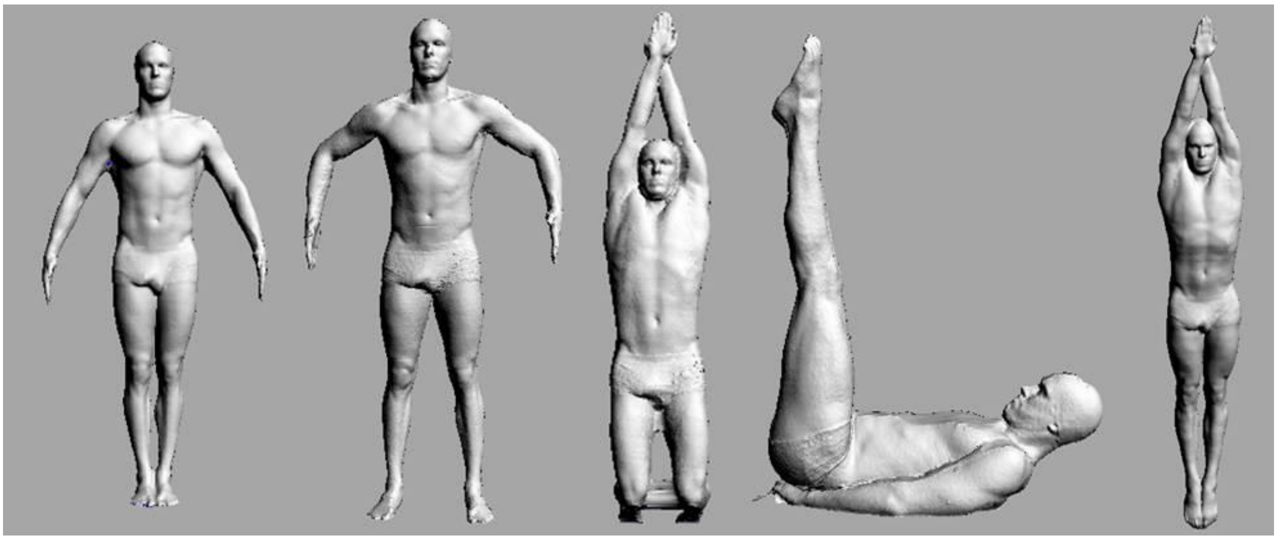
| Towing Condition | Mean and Standard Deviation |
|---|---|
| 1.6 $m.s^{-1}$ | 0.32 ± 0.01 |
| 1.9 $m.s^{-1}$ | 0.39 ± 0.01 |
| 2.0 $m.s^{-1}$ | 0.41 ± 0.01 |
| 2.5 $m.s^{-1}$ | 0.51 ± 0.01 |

**Significant differences between towing conditions for total drag**

| Speed and Depth Combination | Mean Difference (N) | *P* Value | 95% CI Lower Bound | 95% CI Upper Bound |
|---|---|---|---|---|
| 1.6 Surface and 1.9 Surface | -20.46 | 0.00 | -38.09 | -20.84 |
| 1.6 Surface and 1.9 50 | -21.78 | 0.00 | -30.40 | -13.15 |
| 1.6 Surface and 1.9 100 | -18.68 | 0.00 | -27.30 | -10.06 |
| 1.6 Surface and 2.0 Surface | -40.21 | 0.00 | -48.83 | -31.58 |
| 1.6 Surface and 2.0 50 | -31.79 | 0.00 | -40.41 | -23.16 |
| 1.6 Surface and 2.0 100 | -27.82 | 0.00 | -36.44 | -19.19 |
| 1.6 Surface and 2.5 Surface | -121.93 | 0.00 | -130.56 | -113.31 |
| 1.6 Surface and 2.5 50 | -85.45 | 0.00 | -94.08 | -76.83 |
| 1.6 Surface and 2.5100 | -78.09 | 0.00 | -86.71 | -69.46 |
| 1.6 50 and 1.9 Surface | -30.62 | 0.00 | -39.25 | -22.00 |
| 1.6 50 and 1.9 50 | -22.94 | 0.00 | -31.56 | -14.32 |
| 1.6 50 and 1.9 100 | -19.84 | 0.00 | -28.47 | -11.22 |
| 1.6 50 and 2.0 Surface | -41.37 | 0.00 | -50.00 | -32.75 |
| 1.6 50 and 2.0 50 | -32.95 | 0.00 | -41.57 | -24.33 |
| 1.6 50 and 2.0 100 | -28.98 | 0.00 | -37.60 | -20.36 |
| 1.6 50 and 2.5 Surface | -123.10 | 0.00 | -131.72 | -114.47 |
| 1.6 50 and 2.5 50 | -86.62 | 0.00 | -95.24 | -78.00 |
| 1.6 50 and 2.5 100 | -79.25 | 0.00 | -87.88 | -70.63 |
| 1.6 100 and 1.9 Surface | -31.26 | 0.00 | -39.89 | -22.63 |
| 1.6 100 and 1.9 50 | -23.57 | 0.00 | -32.19 | -14.95 |
| 1.6 100 and 1.9 100 | -20.47 | 0.00 | -29.10 | -11.85 |
| 1.6 100 and 2.0 Surface | -42.00 | 0.00 | -50.63 | -33.38 |
| 1.6 100 and 2.0 50 | -33.58 | 0.00 | -42.20 | -24.96 |
| 1.6 100 and 2.0 100 | -29.61 | 0.00 | -38.23 | -20.99 |
| 1.6 100 and 2.5 Surface | -123.73 | 0.00 | -132.35 | -115.10 |
| 1.6 100 and 2.5 50 | -87.25 | 0.00 | -95.87 | -78.62 |
| 1.6 100 and 2.5 100 | -79.88 | 0.00 | -88.51 | -71.26 |
| 1.9 Surface and 1.9 100 | 10.78 | 0.02 | 2.16 | 19.41 |
| 1.9 Surface and 2.0 Surface | -10.75 | 0.02 | -19.37 | -2.12 |
| 1.9 Surface and 2.5 Surface | -92.47 | 0.00 | -101.10 | -83.85 |
| 1.9 Surface and 2.5 50 | -55.99 | 0.00 | -64.62 | -47.37 |
| 1.9 Surface and 2.5 100 | -48.63 | 0.00 | -57.25 | -40.00 |
| 1.9 50 and 2.0 Surface | -18.43 | 0.00 | -27.05 | -9.81 |
| 1.9 50 and 2.0 50 | -10.01 | 0.01 | -18.63 | -1.39 |
| 1.9 50 and 2.5 Surface | -100.16 | 0.00 | -108.78 | -91.53 |
| 1.9 50 and 2.5 50 | -63.68 | 0.00 | -72.30 | -55.05 |
| 1.9 50 and 2.5 100 | -56.31 | 0.00 | -64.94 | -47.69 |
| 1.9 100 and 2.0 Surface | -21.53 | 0.00 | -30.15 | -12.90 |
| 1.9 100 and 2.0 50 | -13.11 | 0.00 | -21.73 | -4.48 |
| 1.9 100 and 2.0 100 | -9.14 | 0.24 | -17.76 | -0.51 |
| 1.9 100 and 2.5 Surface | -103.25 | 0.00 | -111.88 | -94.63 |
| 1.9 100 and 2.5 50 | -66.77 | 0.00 | -75.40 | -58.15 |
| 1.9 100 and 2.5 100 | -59.41 | 0.00 | -68.03 | -50.78 |
| 2.0 Surface and 2.0 100 | 12.392 | 0.00 | 3.77 | 21.02 |
| 2.0 Surface and 2.5 Surface | -81.73 | 0.00 | -90.35 | -73.10 |
| 2.0 Surface and 2.5 50 | -45.24 | 0.00 | -53.87 | -36.62 |
| 2.0 Surface and 2.5 100 | -37.88 | 0.00 | -46.51 | -29.26 |
| 2.0 50 and 2.5 Surface | -90.15 | 0.00 | -98.77 | -81.52 |
| 2.0 50 and 2.5 50 | -53.67 | 0.00 | -62.29 | -45.04 |
| 2.0 50 and 2.5 100 | -46.30 | 0.00 | -54.93 | -37.68 |
| 2.0 100 and 2.5 Surface | -94.12 | 0.00 | -102.74 | -85.49 |
| 2.0 100 and 2.5 50 | -57.64 | 0.00 | -66.26 | -49.01 |
| 2.0 100 and 2.5 100 | -50.27 | 0.00 | -58.90 | -41.65 |
| 2.5 Surface and 2.5 50 | 36.48 | 0.00 | 27.86 | 45.11 |
| 2.5 Surface and 2.5 100 | 43.84 | 0.00 | 35.22 | 52.47 |

**Significant differences between towing conditions for wave drag**

| Speed and Depth Combination | Mean Difference (N) | *P* Value | 95% CI Lower Bound | 95% CI Upper Bound |
|---|---|---|---|---|
| 1.6 Surface and 1.9 Surface | -17.93 | 0.00 | -25.79 | -10.07 |
| 1.6 Surface and 2.0 Surface | -30.09 | 0.00 | -37.95 | -22.22 |
| 1.6 Surface and 2.5 Surface | -71.55 | 0.00 | -79.42 | -20.27 |
| 1.6 Surface and 2.5 Surface | -12.40 | 0.00 | -20.27 | -4.54 |
| 1.6 50 and 1.9 Surface | -23.57 | 0.00 | -31.44 | -15.71 |
| 1.6 50 and 2.0 Surface | -35.73 | 0.00 | -43.60 | -27.87 |
| 1.6 50 and 2.5 Surface | -77.19 | 0.00 | -85.06 | -69.33 |
| 1.6 50 and 2.5 50 | -18.05 | 0.00 | -25.91 | -10.18 |
| 1.6 100 and 1.9 Surface | -24.87 | 0.00 | -32.74 | -17.01 |
| 1.6 100 and 2.0 Surface | -37.03 | 0.00 | -44.90 | -29.17 |
| 1.6 100 and 2.5 Surface | -78.49 | 0.00 | -86.36 | -70.63 |
| 1.6 100 and 2.5 50 | -19.35 | 0.00 | -27.21 | -11.48 |
| 1.9 Surface and 1.9 50 | 20.15 | 0.00 | 12.28 | 28.01 |
| 1.9 Surface and 1.9 100 | 24.39 | 0.00 | 16.53 | 32.26 |
| 1.9 Surface and 2.0 Surface | -12.15 | 0.00 | -20.02 | -4.29 |
| 1.9 Surface and 2.0 50 | 18.04 | 0.00 | 10.18 | 25.91 |
| 1.9 Surface and 2.0 100 | 24.04 | 0.00 | 16.17 | 31.90 |
| 1.9 Surface and 2.5 100 | 21.30 | 0.00 | 13.44 | 29.17 |
| 1.9 50 and 2.0 Surface | -32.30 | 0.00 | -40.17 | -24.44 |
| 1.9 50 and 2.5 Surface | -73.77 | 0.00 | -81.63 | -65.90 |
| 1.9 50 and 2.5 50 | -14.62 | 0.00 | -22.48 | -6.76 |
| 1.9 100 and 2.0 Surface | -36.55 | 0.00 | -44.41 | -28.69 |
| 1.9 100 and 2.5 Surface | -78.01 | 0.00 | -85.88 | -70.15 |
| 1.9 100 and 2.5 50 | -18.86 | 0.00 | -26.73 | -11.00 |
| 2.0 Surface and 2.0 50 | 30.20 | 0.00 | 22.34 | 38.07 |
| 2.0 Surface and 2.0 100 | 36.19 | 0.00 | 28.33 | 44.06 |
| 2.0 Surface and 2.5 Surface | -41.46 | 0.00 | -49.33 | -33.60 |
| 2.0 Surface and 2.5 50 | 17.69 | 0.00 | 9.82 | 25.55 |
| 2.0 Surface and 2.5 100 | 33.46 | 0.00 | 25.60 | 41.33 |
| 2.0 50 and 2.5 Surface | -71.66 | 0.00 | -79.53 | -63.80 |
| 2.0 50 and 2.5 50 | -12.52 | 0.00 | -20.38 | -4.65 |
| 2.0 100 and 2.5 Surface | -77.66 | 0.00 | -85.52 | -69.79 |
| 2.0 100 and 2.5 50 | -18.51 | 0.00 | -26.37 | -10.64 |
| 2.5 Surface and 2.5 50 | 59.15 | 0.00 | 51.28 | 67.01 |
| 2.5 Surface and 2.5 100 | 74.92 | 0.00 | 67.06 | 82.79 |
| 2.5 50 and 2.5 100 | 15.78 | 0.00 | 7.91 | 23.64 |



**Laser Scan positions used in Chapter 8**

## Appendix IV: Extra Technical Information Regarding the Towing Device and Acoustic Sensors

### Technical Elements of Towing System

The dynamometer used for towing in Chapter 8 was developed in the Netherlands by Motor Power Company. An AIS internal technical review was conducted prior to testing to determine the accuracy and validity of the towing system. A comparison between the dynamometer speeds and speeds recorded by the Swimtrak timing system was conducted by towing a swimmer in the streamlined position. The range of speeds used were the same as the speeds used during testing in Chapter 8. The correlations between the towing speeds and the speeds calculated using segmented split timing from Swimtrak revealed a 0.99 correlation. Furthermore, the same process was conducted over a number trials to ensure the speed values were reproducible.

The dynamometer was also used to calculate total drag force. Calibration of the device was conducted prior to testing for a range of 0-500 N by simultaneously comparing the force measured from the dynamometer with force measured by a Kistler force plate. The dynamometer calculated the value of force based on the amount of work needed to maintain the drum moving at a constant speed which was pre-set according to the speed needed for testing in Chapter 8. The raw signal from the dynamometer was then sent through an A-D converter (ADInstruments Powerlab) with a 24 bit resolution and linearity of ± 0.0006% FSR before the trace was inputted and analysed using LabChart Pro. The dynamometer raw signal was ± 10 V which was converted to ± 500 N. The force measure value was then used to calculated total drag for each towing condition.

## Technical Elements of Acoustic Sensors

Acoustic sensors have been widely used previously to measure waves. The acoustic sensors used in the experiment in Chapter 8 were made by ToughSonic. The sensors transmit an acoustic pulse at 10 hz and detect flat or curved objects such as waves. The surface or water then reflects ultrasound back to the sensor and the height of the object in question is able to be determined based on the speed of the return signal. The sensors have been tested for repeatability at a rate of 0.03% at constant temperature. The testing session were conducted over two days where water and atmospheric temperature were kept as constant as possible to decrease interference with the sensors. The information the sensors was then coupled with specialised Matlab code to calculate wave drag.

## Wave drag Calculations

The specialised Matlab code used to calculate wave drag were developed through research involving ship wave resistance. There are a number of different methods that have been used in the past, however in this thesis the longitudinal cut method (LWC) was utilised. While the mathematical theory of this method is largely beyond the scope of this thesis, the LWC method involves the measurement of one or more wave profiles along a straight track parallel to the direction of motion of the ship or swimmer. The equations (Shown Below) required the input of sine and cosine components of the free wave-spectrum calculated from the acoustic sensors, before Fourier transformations of each longitudinal cut were used to give the value of wave drag. The LWC method does not take into account the wave reflection from walls during testing, hence to overcome this testing was conducted in the centre of the pool with all lane ropes removed. A detailed description and example of the specific mathematical calculations can be found in Eggers, Sharma, and Ward (1967).

$$F(u) = \frac{4}{w(2w^2 - 1)} \{C_\nu(w, y) \cos (uy) - S_\nu(w, y) \sin (uy)\}$$

$$G(u) = \frac{-4}{w(2w^2 - 1)} \{C_\nu(w, y) \sin (uy) + S_\nu(w, y) \cos (uy)\} \quad (36)$$

$$R_w = \frac{1}{\pi} \int_0^\infty \{(C^*)^2 + (S^*)^2\} \frac{du}{w^2(2w^2 - 1)} \quad (44)$$

**LWC equations from Eggers et al. 1967**

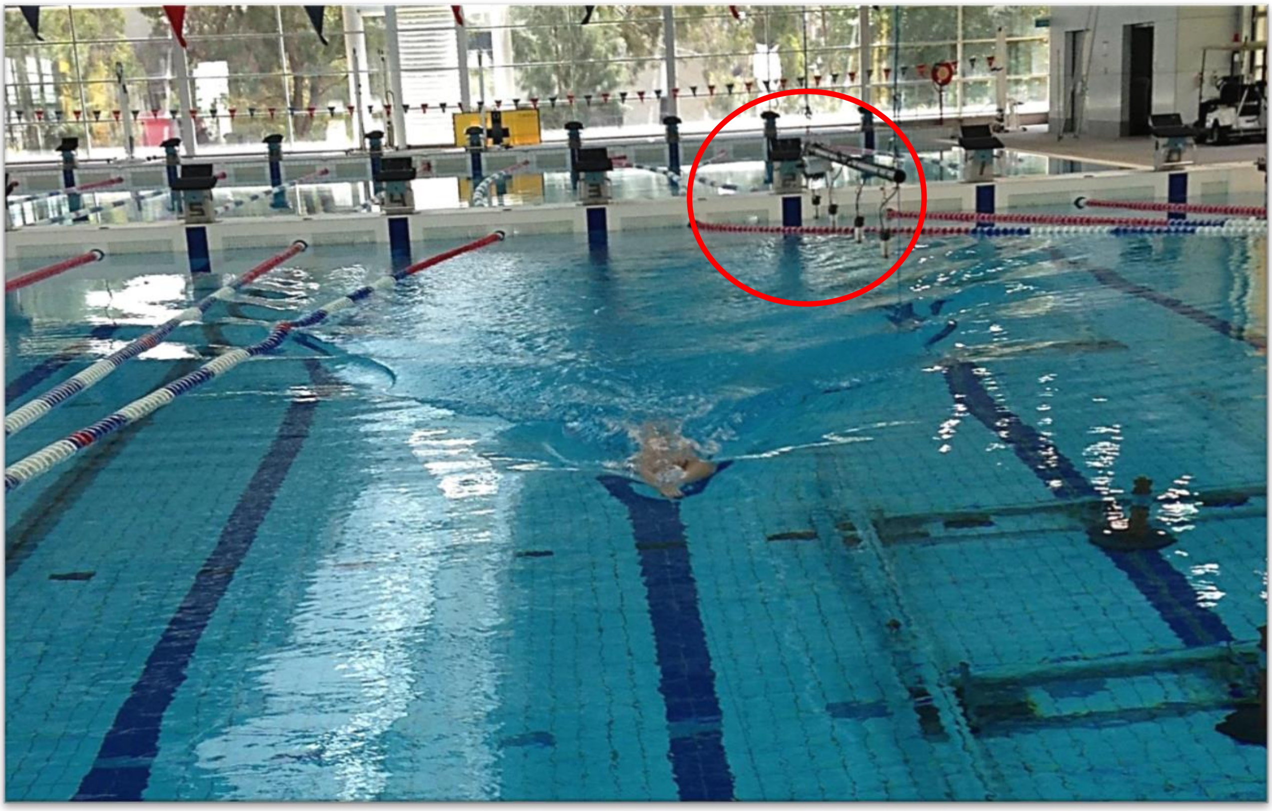


**Diagram of the acoustic sensor set-up during towing testing in Chapter 8**

## Appendix V: Chapter 9 Descriptive Statistic Tables for Each Subject

**Subject 1**

| Testing Session | Reaction Time (s) | Take-off Hor. Vel. ($m.s^{-1}$) | Head Entry Time (s) | Head Entry Distance (m) | Entry Angle (°) |
|---|---|---|---|---|---|
| **Pre-Test** | 0.71 ± 0.03 | 4.52 ± 0.06 | 1.11 ± 0.04 | 3.08 ± 0.03 | 49.32 ± 0.47 |
| **Post –Test** | 0.71 ± 0.03 | 4.29 ± 0.08 | 1.12 ± 0.03 | 3.17 ± 0.03 | 50.90 ± 0.55 |
| **Ret.-Test** | 0.73 ± 0.01 | 4.36 ± 0.05 | 1.10 ± 0.02 | 3.06 ± 0.04 | 49.85 ± 0.68 |

| Testing Session | Avg. Vel. 0-5 ($m.s^{-1}$) | Avg. Vel. 5-7.5 ($m.s^{-1}$) | Avg. Vel. 7.5 -10 ($m.s^{-1}$) | Avg. Vel. 10-15 ($m.s^{-1}$) | Time to 5 m (s) |
|---|---|---|---|---|---|
| **Pre-Test** | 3.15 ± 0.08 | 2.34 ± 0.05 | 1.66 ± 0.03 | 1.63 ± 0.03 | 1.59 ± 0.04 |
| **Post –Test** | 3.18 ± 0.08 | 2.34 ± 0.09 | 1.74 ± 0.06 | 1.66 ± 0.01 | 1.58 ± 0.04 |
| **Ret.-Test** | 3.15 ± 0.04 | 2.32 ± 0.05 | 1.62 ± 0.03 | 1.69 ± 0.05 | 1.58 ± 0.02 |

| Testing Session | Time to 7.5 m (s) | Time to 10 m (s) | Time to 15 m (s) | Max Depth (m) | Time of Max Depth (s) |
|---|---|---|---|---|---|
| **Pre-Test** | 2.66 ± 0.04 | 4.16 ± 0.04 | 7.23 ± 0.07 | -0.97 ± 0.09 | 2.06 ± 0.08 |
| **Post –Test** | 2.65 ± 0.06 | 4.09 ± 0.08 | 7.10 ± 0.08 | -0.79 ± 0.03 | 1.77 ± 0.38 |
| **Ret.-Test** | 2.67 ± 0.03 | 4.21 ± 0.04 | 7.17 ± 0.10 | -0.81 ± 0.05 | 1.81 ± 0.13 |

| Testing Session | Distance of Max Depth (m) | Time of 1st Kick (s) | Breakout Distance (m) | Breakout Time (s) | Depth of 1st Kick (m) |
|---|---|---|---|---|---|
| **Pre-Test** | 6.41 ± 0.13 | 2.53 ± 0.05 | 11.26 ± 0.54 | 4.76 ± 0.29 | -1.05 ± 0.14 |
| **Post –Test** | 5.69 ± 0.13 | 2.35 ± 0.07 | 10.28 ± 0.31 | 5.28 ± 0.75 | -0.81 ± 0.36 |
| **Ret.-Test** | 5.73 ± 0.33 | 2.36 ± 0.05 | 10.46 ± 0.25 | 4.51 ± 0.37 | -0.82 ± 0.13 |

| Testing Session | Distance of 1st Kick (m) | Time UW in Descent (s) | Time UW in Ascent (s) | Total UW Time (s) | Avg. UW Vel. ($m.s^{-1}$) |
|---|---|---|---|---|---|
| **Pre-Test** | 5.29 ± 0.27 | 0.95 ± 0.06 | 3.00 ± 0.34 | 3.96 ± 0.29 | 2.07 ± 0.02 |
| **Post –Test** | 6.47 ± 0.11 | 0.66 ± 0.13 | 2.57 ± 0.15 | 3.22 ± 0.14 | 2.21 ± 0.03 |
| **Ret.-Test** | 5.05 ± 0.24 | 0.71 ± 0.12 | 2.68 ± 0.05 | 3.39 ± 0.11 | 2.18 ± 0.02 |

| Subject 2 | | | | | |
|---|---|---|---|---|---|
| **Testing Session** | **Reaction Time (s)** | **Take-off Hor. Vel. ($m \cdot s^{-1}$)** | **Head Entry Time (s)** | **Head Entry Distance (m)** | **Entry Angle (°)** |
| **Pre-Test** | 0.73 ± 0.01 | 4.36 ± 0.11 | 1.07 ± 0.02 | 2.81 ± 0.04 | 50.85 ± 0.70 |
| **Post –Test** | 0.78 ± 0.03 | 3.96 ± 0.05 | 1.15 ± 0.03 | 2.80 ± 0.05 | 51.62 ± 0.47 |
| **Ret.-Test** | 0.78 ± 0.01 | 3.93 ± 0.05 | 1.15 ± 0.01 | 2.74 ± 0.04 | 51.98 ± 0.86 |
| **Testing Session** | **Avg. Vel. 0-5 ($m \cdot s^{-1}$)** | **Avg. Vel. 5-7.5 ($m \cdot s^{-1}$)** | **Avg. Vel. 7.5 -10 ($m \cdot s^{-1}$)** | **Avg. Vel. 10-15 ($m \cdot s^{-1}$)** | **Time to 5 m (s)** |
| **Pre-Test** | 2.73 ± 0.06 | 1.97 ± 0.06 | 1.65 ± 0.03 | 1.65 ± 0.01 | 1.83 ± 0.04 |
| **Post –Test** | 2.65 ± 0.07 | 1.89 ± 0.05 | 1.57 ± 0.05 | 1.60 ± 0.05 | 1.89 ± 0.05 |
| **Ret.-Test** | 2.64 ± 0.04 | 1.90 ± 0.04 | 1.64 ± 0.04 | 1.60 ± 0.05 | 1.89 ± 0.03 |
| **Testing Session** | **Time to 7.5 m (s)** | **Time to 10 m (s)** | **Time to 15 m (s)** | **Max Depth (m)** | **Time of Max Depth (s)** |
| **Pre-Test** | 3.10 ± 0.06 | 4.62 ± 0.09 | 7.65 ± 0.08 | -1.05 ± 0.13 | 1.63 ± 0.13 |
| **Post –Test** | 3.21 ± 0.05 | 4.81 ± 0.08 | 7.94 ± 0.16 | -1.12 ± 0.12 | 1.98 ± 0.12 |
| **Ret.-Test** | 3.21 ± 0.05 | 4.74 ± 0.09 | 7.87 ± 0.13 | -0.92 ± 0.12 | 1.88 ± 0.13 |
| **Testing Session** | **Distance of Max Depth (m)** | **Time of 1st Kick (s)** | **Breakout Distance (m)** | **Breakout Time (s)** | **Depth of 1st Kick (m)** |
| **Pre-Test** | 4.58 ± 0.33 | 1.93 ± 0.13 | 10.22 ± 0.41 | 4.76 ± 0.29 | -1.05 ± 0.14 |
| **Post –Test** | 5.30 ± 0.29 | 2.59 ± 0.11 | 10.48 ± 1.02 | 5.28 ± 0.75 | -0.81 ± 0.36 |
| **Ret.-Test** | 5.05 ± 0.25 | 2.40 ± 0.17 | 9.68 ± 0.46 | 4.51 ± 0.37 | -0.82 ± 0.13 |
| **Testing Session** | **Distance of 1st Kick (m)** | **Time UW in Descent (s)** | **Time UW in Ascent (s)** | **Total UW Time (s)** | **Avg. UW Vel. ($m \cdot s^{-1}$)** |
| **Pre-Test** | 5.29 ± 0.27 | 0.55 ± 0.13 | 3.13 ± 0.26 | 3.68 ± 0.29 | 2.02 ± 0.06 |
| **Post –Test** | 6.47 ± 0.11 | 0.83 ± 0.12 | 3.30 ± 0.71 | 4.14 ± 0.73 | 1.87 ± 0.18 |
| **Ret.-Test** | 6.10 ± 0.24 | 0.73 ± 0.14 | 2.63 ± 0.25 | 3.36± 0.37 | 2.07 ± 0.09 |

| Subject 3 | | | | | |
|---|---|---|---|---|---|
| **Testing Session** | **Reaction Time (s)** | **Take-off Hor. Vel. ($m \cdot s^{-1}$)** | **Head Entry Time (s)** | **Head Entry Distance (m)** | **Entry Angle (°)** |
| **Pre-Test** | 0.69 ± 0.02 | 4.79 ± 0.07 | 1.05 ± 0.02 | 2.81 ± 0.04 | 48.40 ± 0.70 |
| **Post –Test** | 0.71 ± 0.02 | 4.61 ± 0.04 | 1.09 ± 0.02 | 2.80 ± 0.05 | 47.60 ± 0.49 |
| **Ret.-Test** | 0.75 ± 0.01 | 4.63 ± 0.03 | 1.13 ± 0.01 | 2.74 ± 0.04 | 47.13 ± 0.50 |
| **Testing Session** | **Avg. Vel. 0-5 ($m \cdot s^{-1}$)** | **Avg. Vel. 5-7.5 ($m \cdot s^{-1}$)** | **Avg. Vel. 7.5 -10 ($m \cdot s^{-1}$)** | **Avg. Vel. 10-15 ($m \cdot s^{-1}$)** | **Time to 5 m (s)** |
| **Pre-Test** | 3.37 ± 0.03 | 2.83 ± 0.08 | 2.01 ± 0.03 | 1.90 ± 0.02 | 1.48 ± 0.01 |
| **Post –Test** | 3.32 ± 0.05 | 2.72 ± 0.09 | 1.95 ± 0.06 | 1.87 ± 0.02 | 1.51 ± 0.02 |
| **Ret.-Test** | 3.24 ± 0.03 | 2.75 ± 0.06 | 2.00 ± 0.04 | 1.90 ± 0.04 | 1.55 ± 0.02 |
| **Testing Session** | **Time to 7.5 m (s)** | **Time to 10 m (s)** | **Time to 15 m (s)** | **Max Depth (m)** | **Time of Max Depth (s)** |
| **Pre-Test** | 2.37 ± 0.04 | 3.61 ± 0.05 | 6.25 ± 0.08 | -0.78 ± 0.06 | 1.51 ± 0.09 |
| **Post –Test** | 2.42 ± 0.03 | 3.71 ± 0.07 | 6.38 ± 0.10 | -0.79 ± 0.03 | 1.60 ± 0.08 |
| **Ret.-Test** | 2.45 ± 0.03 | 3.70 ± 0.06 | 6.34 ± 0.09 | -0.78 ± 0.05 | 1.63 ± 0.03 |
| **Testing Session** | **Distance of Max Depth (m)** | **Time of 1st Kick (s)** | **Breakout Distance (m)** | **Breakout Time (s)** | **Depth of 1st Kick (m)** |
| **Pre-Test** | 5.18 ± 0.34 | 2.24 ± 0.13 | 11.86 ± 0.25 | 4.68 ± 0.14 | -0.69 ± 0.06 |
| **Post –Test** | 5.42 ± 0.26 | 2.15 ± 0.06 | 10.52 ± 0.10 | 4.00 ± 0.12 | -0.69 ± 0.06 |
| **Ret.-Test** | 5.39 ± 0.11 | 2.30 ± 0.04 | 10.63 ± 0.27 | 4.06 ± 0.15 | -0.68 ± 0.04 |
| **Testing Session** | **Distance of 1st Kick (m)** | **Time UW in Descent (s)** | **Time UW in Ascent (s)** | **Total UW Time (s)** | **Avg. UW Vel. ($m.s^{-1}$)** |
| **Pre-Test** | 7.23 ± 0.27 | 0.46 ± 0.09 | 3.17 ± 0.18 | 3.62 ± 0.12 | 2.41 ± 0.06 |
| **Post –Test** | 6.94 ± 0.12 | 0.51 ± 0.08 | 2.41 ± 0.06 | 2.91 ± 0.11 | 2.51 ± 0.18 |
| **Ret.-Test** | 7.20 ± 0.11 | 0.50 ± 0.03 | 2.43 ± 0.16 | 2.93 ± 0.15 | 2.54 ± 0.09 |

## Appendix VI: AIS Performance Research – Ethics Approval (All Chapters)

**Australian Institute of Sport**

**MINUTE**

| | | | |
|---|---|---|---|
| **TO:** | Ms Elaine Tor | **CC:** | |
| **FROM:** | Ms Helene Rushby | | |
| **SUBJECT:** | Approval from AIS Ethics Committee | **DATE:** | 21st May 2012 |

On the 21st of May 2012, the AIS Ethics Committee Secretary gave consideration to your submission titled ***"Quantifying the underwater phase of a swimming start".*** The Secretary saw no ethical reason why your project should not proceed.

The approval number for this project: 20120502

It is a requirement of the AIS Ethics Committee that the Principal Researcher (you) advise all researchers involved in the study of Ethics Committee approval and any conditions of that approval. You are also required to advise the Ethics Committee immediately (via the Secretary) of:

any proposed changes to the research design,
any adverse events that may occur,

Researchers are required to submit **annual status reports** and **final reports** to the secretary of the AIS Ethics Committee. Details of status report requirements are contained in the "Guidelines" for ethics submissions.

If you have any questions regarding this matter, please don't hesitate to contact me on (02) 6214 1577.

Sincerely
Helene Rushby
Secretary, AIS EC

**Australian Institute of Sport**

**MINUTE**

| | | | |
|---|---|---|---|
| TO: | Ms Elaine Tor | CC: | |
| FROM: | Ms Helene Rushby | | |
| SUBJECT: | Approval from AIS Ethics Committee | DATE: | 17th December 2012 |

On the 11th of December 2012, the AIS Ethics Committee gave consideration to your submission titled "**Comparing three common underwater trajectories**". The Committee saw no ethical reason why your project should not proceed.

The approval number for this project: 20121202

It is a requirement of the AIS Ethics Committee that the Principal Researcher (you) advise all researchers involved in the study of Ethics Committee approval and any conditions of that approval. You are also required to advise the Ethics Committee immediately (via the Secretary) of:

Any proposed changes to the research design,
Any adverse events that may occur,

Researchers are required to submit **annual status reports** and **final reports** to the secretary of the AIS Ethics Committee. Details of status report requirements are contained in the "Guidelines" for ethics submissions.

If you have any questions regarding this matter, please don't hesitate to contact me on (02) 6214 1577

Sincerely
Helene Rushby
Secretary, AIS EC

**Australian Institute of Sport**

**MINUTE**

| | | | |
|---|---|---|---|
| TO: | Ms Elaine Tor | CC: | |
| FROM: | Ms Helene Rushby | | |
| SUBJECT: | Approval from AIS Ethics Committee | DATE: | 17th December 2012 |

On the 11th of December 2012, the AIS Ethics Committee gave consideration to your submission titled "**What are the effects of wave drag and anthropometric characteristics on the underwater phase of a start**". The Committee saw no ethical reason why your project should not proceed.

The approval number for this project: 20121201

It is a requirement of the AIS Ethics Committee that the Principal Researcher (you) advise all researchers involved in the study of Ethics Committee approval and any conditions of that approval. You are also required to advise the Ethics Committee immediately (via the Secretary) of:

Any proposed changes to the research design,
Any adverse events that may occur,

Researchers are required to submit **annual status reports** and **final reports** to the secretary of the AIS Ethics Committee. Details of status report requirements are contained in the "Guidelines" for ethics submissions.

If you have any questions regarding this matter, please don't hesitate to contact me on (02) 6214 1577

Sincerely
Helene Rushby
Secretary, AIS EC

**Australian Institute of Sport**

**MINUTE**

| | | | |
|---|---|---|---|
| TO: | Ms Elaine Tor | CC: | |
| FROM: | Ms Helene Rushby | | |
| SUBJECT: | Approval from AIS Ethics Committee | DATE: | 13th February 2014 |

On the 11th April 2014, the AIS Ethics Committee gave consideration to the minor variations put forward for your submission titled **"Using feedback to start performance".** The Committee saw no ethical reason why your project should not proceed.

The approval number for this project remains as: 20131201

It is a requirement of the AIS Ethics Committee that the Principal Researcher (you) advise all researchers involved in the study of Ethics Committee approval and any conditions of that approval. You are also required to advise the Ethics Committee immediately (via the Secretary) of:

Any proposed changes to the research design,
Any adverse events that may occur,

Researchers are required to submit **annual status reports** and **final reports** to the secretary of the AIS Ethics Committee. Details of status report requirements are contained in the "Guidelines" for ethics submissions.

Please note the approval for this submission expires on the 30th June 2015 after which time an extension will need to be sought.

If you have any questions regarding this matter, please don't hesitate to contact me on (02) 6214 1577

Sincerely
Heléne Rushby
Secretary, AIS EC

**Appendix VII: Informed Consent Forms**

**'INFORMED CONSENT' FORM (Adult)**

**Project Title:** Comparing three common underwater trajectories.

**Principal Researchers:** Elaine Tor, Dr. David Pease, Dr. Kevin Ball

This is to certify that I,_______________________________________________ hereby agree to participate as a volunteer in a scientific investigation as an authorized part of the research program of the Australian Sports Commission under the supervision of Elaine Tor.

The investigation and my part in the investigation have been defined and fully explained to me by Elaine Tor and I understand the explanation. A copy of the procedures of this investigation and a description of any risks and discomforts has been provided to me and has been discussed in detail with me.

- I have been given an opportunity to ask whatever questions I may have had and all such questions and inquiries have been answered to my satisfaction.

- I understand that I am free to deny any answers to specific items or questions in interviews or questionnaires.

- I understand that I am free to withdraw consent and to discontinue participation in the project or activity at any time, without disadvantage to myself.

- I understand that I am free to withdraw my data from analysis without disadvantage to myself.

- I understand that any data or answers to questions will remain confidential with regard to my identity.

- I certify to the best of my knowledge and belief, I have no physical or mental illness or weakness that would increase the risk to me of participating in this investigation.

- I am participating in this project of my (his/her) own free will and I have not been coerced in any way to participate.

Signature of Subject: ________________________________ Date: ___/___/___

I, the undersigned, was present when the study was explained to the subject/s in detail and to the best of my knowledge and belief it was understood.

Signature of Researcher: ______________________________ Date: ___/___/___

**'INFORMED CONSENT' FORM (Minor)**

**Project Title:** Comparing three common underwater trajectories.

**Principal Researchers:** Elaine Tor, Dr. David Pease, Dr. Kevin Ball

This is to certify that I, ___________________________________________ hereby agree to give permission to have my child participate as a volunteer in a scientific investigation as an authorised part of the research program of the Australian Sports Commission under the supervision of Elaine Tor.

The investigation and my child's part in the investigation have been defined and fully explained to me by Elaine Tor and I understand the explanation. A copy of the procedures of this investigation and a description of any risks and discomforts has been provided to me and has been discussed in detail with me.

- I have been given an opportunity to ask whatever questions I may have had and all such questions and inquiries have been answered to my satisfaction.

- I understand that I am free to deny any answers to specific items or questions in interviews or questionnaires.

- I understand that my child is free to withdraw consent and to discontinue participation in the project or activity at any time, without disadvantage to myself.

- I understand that I am free to withdraw my data from analysis without disadvantage to myself.

- I understand that any data or answers to questions will remain confidential with regard to my child's identity.

- I certify to the best of my knowledge and belief, my child has no physical or mental illness or weakness that would increase the risk to me (him/her) of participating in this investigation.

- My child is participating in this project of my (his/her) own free will and My child has) not been coerced in any way to participate.

Signature of Subject: ______________________________ Date: ___/___/___

Signature of Parent or
Guardian of minor: (under 18 years) ______________________ Date: ___/___/___

I, the undersigned, was present when the study was explained to the subject/s in detail and to the best of my knowledge and belief it was understood.
Signature of Researcher: ____________________________ Date: ___/___/___

**'INFORMED CONSENT' FORM (Adult)**

**Project Title:** What are the effects of wave drag and anthropometric characteristics on the underwater phase of a start?

**Principal Researchers:** Elaine Tor, Dr. David Pease, Dr. Kevin Ball

This is to certify that I,_______________________________________________ hereby agree to participate as a volunteer in a scientific investigation as an authorized part of the research program of the Australian Sports Commission under the supervision of Elaine Tor.

The investigation and my part in the investigation have been defined and fully explained to me by Elaine Tor and I understand the explanation. A copy of the procedures of this investigation and a description of any risks and discomforts has been provided to me and has been discussed in detail with me.

- I have been given an opportunity to ask whatever questions I may have had and all such questions and inquiries have been answered to my satisfaction.
- I understand that I am free to deny any answers to specific items or questions in interviews or questionnaires.
- I understand that I am free to withdraw consent and to discontinue participation in the project or activity at any time, without disadvantage to myself.
- I understand that I am free to withdraw my data from analysis without disadvantage to myself.
- I understand that any data or answers to questions will remain confidential with regard to my identity.
- I certify to the best of my knowledge and belief, I have no physical or mental illness or weakness that would increase the risk to me of participating in this investigation.
- I am participating in this project of my (his/her) own free will and I have not been coerced in any way to participate.

Signature of Subject: ________________________________ Date: ___/___/___

I, the undersigned, was present when the study was explained to the subject/s in detail and to the best of my knowledge and belief it was understood.

Signature of Researcher: ______________________________ Date: ___/___/___

**‘INFORMED CONSENT’ FORM (Minor)**

**Project Title:** What are the effects of wave drag and anthropometric characteristics on the underwater phase of a start?

**Principal Researchers:** Elaine Tor, Dr. David Pease, Dr. Kevin Ball

This is to certify that I, ___________________________________________ hereby agree to give permission to have my child participate as a volunteer in a scientific investigation as an authorised part of the research program of the Australian Sports Commission under the supervision of Elaine Tor.

The investigation and my child’s part in the investigation have been defined and fully explained to me by Elaine Tor and I understand the explanation. A copy of the procedures of this investigation and a description of any risks and discomforts has been provided to me and has been discussed in detail with me.

- I have been given an opportunity to ask whatever questions I may have had and all such questions and inquiries have been answered to my satisfaction.
- I understand that I am free to deny any answers to specific items or questions in interviews or questionnaires.
- I understand that my child is free to withdraw consent and to discontinue participation in the project or activity at any time, without disadvantage to myself.
- I understand that I am free to withdraw my data from analysis without disadvantage to myself.
- I understand that any data or answers to questions will remain confidential with regard to my child’s identity.
- I certify to the best of my knowledge and belief, my child has no physical or mental illness or weakness that would increase the risk to me (him/her) of participating in this investigation.
- My child is participating in this project of my (his/her) own free will and My child has) not been coerced in any way to participate.

Signature of Subject: ______________________________ Date: ___/___/___

Signature of Parent or
Guardian of minor: (under 18 years) ______________________ Date: ___/___/___

I, the undersigned, was present when the study was explained to the subject/s in detail and to the best of my knowledge and belief it was understood.
Signature of Researcher: ____________________________ Date: ___/___/___

**‘INFORMED CONSENT’ FORM (Minor)**

Project Title: Using feedback to improve swimming start performance

Principal Researchers: Elaine Tor, Dr David Pease, Dr Kevin Ball

This is to certify that I, hereby agree to give permission to have my child participate as a volunteer in a scientific investigation as an authorised part of the research program of the Australian Sports Commission under the supervision of Elaine Tor.

The investigation and my child’s part in the investigation have been defined and fully explained to me by Elaine Tor and I understand the explanation. A copy of the procedures of this investigation and a description of any risks and discomforts has been provided to me and has been discussed in detail with me.

- I have been given an opportunity to ask whatever questions my child or myself may have had and all such questions and inquiries have been answered to my satisfaction.

- I understand that my child is free to deny any answers to specific items or questions in interviews or questionnaires.

- I understand that my child is free to withdraw consent and to discontinue participation in the project or activity at any time, without disadvantage.

- I understand that my child is free to withdraw his/her data from analysis without disadvantage.

- I understand that any data or answers to questions will remain confidential with regard to my child’s identity.

- I certify to the best of my knowledge and belief, my child has no physical or mental illness or weakness that would increase the risk to me (him/her) of participating in this investigation.

- My child is participating in this project of my (his/her) own free will and My child has) not been coerced in any way to participate.

Signature of Subject: ________________________________ Date: ___/___/___

Signature of Parent or
Guardian of minor: (under 18 years) _______________________ Date: ___/___/___

I, the undersigned, was present when the study was explained to the subject/s in detail and to the best of my knowledge and belief it was understood.

Signature of Researcher: ______________________________ Date: ___/___/___

**‘INFORMED CONSENT’ FORM (Adult)**

Project Title: Using feedback to improve swimming start performance

Principal Researchers: Elaine Tor, Dr David Pease, Dr Kevin Ball

This is to certify that I, hereby agree to participate as a volunteer in a scientific investigation as an authorised part of the research program of the Australian Sports Commission under the supervision of Elaine Tor.

The investigation and my part in the investigation have been defined and fully explained to me by Elaine Tor and I understand the explanation. A copy of the procedures of this investigation and a description of any risks and discomforts has been provided to me and has been discussed in detail with me.

- I have been given an opportunity to ask whatever questions I may have had and all such questions and inquiries have been answered to my satisfaction.
- I understand that I am free to deny any answers to specific items or questions in interviews or questionnaires.
- I understand that I am free to withdraw consent and to discontinue participation in the project or activity at any time, without disadvantage to myself.
- I understand that I am free to withdraw my data from analysis without disadvantage to myself.
- I understand that any data or answers to questions will remain confidential with regard to my identity.
- I certify to the best of my knowledge and belief, I have no physical or mental illness or weakness that would increase the risk to me of participating in this investigation.
- I am participating in this project of my (his/her) own free will and I have not been coerced in any way to participate.

Signature of Subject: ________________________________ Date: ___/___/___

I, the undersigned, was present when the study was explained to the subject/s in detail and to the best of my knowledge and belief it was understood.

Signature of Researcher: ______________________________ Date: ___/___/___

**Appendix VIII: Information to Participant Forms**

# Information to Participants

**Study title:** Comparing three common underwater trajectories.

**Researchers** Elaine Tor (AIS/VU)
Dr David Pease (AIS)
Dr Kevin Ball (VU)

**Background**
To perform a good swimming start swimmers must learn to maximise their initial velocity on entry and minimize their resistance during the glide phase of the swimming start. There are currently few studies that explore effective methods for maintaining average velocity following the flight phase of the start. With the recent standardisation of swim suits by FINA swimmers will have to rely on gaining performance advantages from elements that can be control by themselves. These elements during the start include depth of dive entry, underwater kick and angle of breakout. With knowledge of the precise values of these elements swimmers and coaches will be able specifically train to meet these values and obtain better start performances in the future. Therefore, the aim of this study is to determine if there is an optimal underwater trajectory which swimmers must use to maintain their velocity on entry into the water.

**Aim of the study**

- **To determine which of the three most common underwater trajectories is the best.**

**Study protocols**
You will be asked to perform a series of dives at controlled depths. The depths will be categorised as "shallow", "flat", "deep" and normal. You will perform 16 dives over two testing sessions (four dives at set depths and three self-selected dives) with three minutes rest in between each dive at randomized depths. To control for each of the different gliding paths you will be asked to surface at specific colored markers that will be placed at the bottom of the pool. You will also be given practice trials prior to testing to ensure you able to perform the dives as required. Wetplate will during each trial to collect the data for further analysis.

**Potential discomforts and risks**
There are no added discomforts and risks associated with participating in this study as all trials will be incorporated in your training programs as part of servicing as specified by your coach.

**Right of Withdrawal**
You should understand that participation in this study is completely voluntary. You can choose to withdraw at any stage or time in the process without any consequence. By signing the informed consent you are indicating that the tests and procedures of this study have been explained to you and understood by you.

**Confidentiality**
All information given by you will be stored on a password protected computer or filed with restricted access at the AIS. All information presented for publication will remain anonymous

and reports generated from the analysis of each trial will only be distributed to you and your coach.

This study is being conducted in conjunction with a PhD Project. A report of the study will be submitted as a PhD thesis and presented in scientific publications and at seminars; therefore individual participants will not be identifiable in such a report.

**Enquiries**
If you have any enquires regarding requirements and procedures used in this study or would like further information please do not hesitate to contact the investigators.

| | |
|---|---|
| Elaine Tor | (02) 6214 1915 |
| Dr David Pease | (02) 6214 1732 |

**If you have any concerns with respect to the conduct of this study, you may contact the Secretary of the AIS Ethics Committee (Ms Helene Rushby) 02 6214 1577**.

# Information to Participants

**Study title:** What are the effects of wave drag and anthropometric characteristics on the underwater phase of a start?

**Researchers** Elaine Tor (AIS/VU)
Dr David Pease (AIS)
Dr Kevin Ball (VU)

**Background**
The main resistive force in swimming is drag. Drag acts opposite to the direction of the motion of the body and is highly related to the flow around the body. There are four main forms of drag; passive drag, friction (or skin) drag, form drag and wave drag (Lyttle et al., 1998; Naemi et al., 2010; Naemi & Sanders, 2008; Vennell et al., 2006). There are multiple research papers which suggest that wave drag is the largest component of drag when travelling at the surface of the water (Vennell et al., 2006). Wave drag is mainly due to energy needed to create the transverse and divergent waves which lie within a 39 degree sector behind the vessel or swimmer (Vennell et al., 2006). With this in mind it is necessary to determine how wave drag affects the swimmer as they rise to the surface following a dive start.

**Aim of the study**

- **To determine the effects of wave drag on the underwater phase of a swimming start.**
- **To determine how different body shapes affect wave drag estimations during the start phase of swimming**

**Study protocols**
Prior to testing each you will be full body scanned using a 3D full body laser scanner. You will be scanned wearing only your swimmers and swimming cap. Following the laser scan you will be also asked to perform three maximal 25 m underwater kick trials to determine maximal underwater kicking speed. You will then be towed using a dynamometer mounted on top of a force platform while acoustic proximity sensors, mounted approximately 0.9 m above the pool surface will measure the amount of wave drag. Swimmers will be towed at controlled depths or 0.5 m, 1.0 m and surface. The velocities used will be between 1.5 m/s and 2.5 m/s to mimic the speeds you travel at as you enter the water follow a dive start. You will be given time to familiarize yourself with the testing protocol before you will be towed once at each depth at four different speeds, equalling 12 tows in total. Total testing time for participation in this study will be two hours.

**Potential discomforts and risks**
There are no added discomforts and risks associated with participating in this study as all trials will be incorporated in your training programs as part of servicing as specified by your coach.

**Right of Withdrawal**
You should understand that participation in this study is completely voluntary. You can choose to withdraw at any stage or time in the process without any consequence. By signing the

informed consent you are indicating that the tests and procedures of this study have been explained to you and understood by you.

**Confidentiality**

All information given by you will be stored on a password protected computer or filed with restricted access at the AIS. All information presented for publication will remain anonymous and reports generated from the analysis of each trial will only be distributed to you and your coach.

This study is being conducted in conjunction with a PhD Project. A report of the study will be submitted as a PhD thesis and presented in scientific publications and at seminars; therefore individual participants will not be identifiable in such a report.

**Enquiries**

If you have any enquires regarding requirements and procedures used in this study or would like further information please do not hesitate to contact the investigators.

| | |
|---|---|
| Elaine Tor | (02) 6214 1915 |
| Dr David Pease | (02) 6214 1732 |

**If you have any concerns with respect to the conduct of this study, you may contact the Secretary of the AIS Ethics Committee (Ms Helene Rushby) 02 6214 1577**.

# Information to Participants

**Study title:** Using feedback to improve swimming start performance

**Researchers** Elaine Tor (AIS/VU)
Dr David Pease (AIS)
Prof Damian Farrow (VU/AIS)
Dr Kevin Ball (VU)

**Background**

Delivering high quality and frequent augmented feedback has been shown as one method to reduce errors and increase the efficiency of athletes' performance during skill acquisition. Therefore, using the results from a number of previous studies which have determined the ideal underwater trajectory based on the relationship between velocity, depth, drag and anthropometric characteristics, this study aims to use biomechanical feedback to improve start performance.

**Aims of the study**

- **To determine if biomechanical feedback can be used to improve swimming start performance.**

**Study protocols**

Prior to testing you will be asked to fill in a number of questionnaires to the best of your ability. These questionnaires will assist with data interpretation and assist you coach to improve your learning environment in the future. There will be a pre-test followed by a four-week intervention phase before a post-test and finally a retention test after another two-week period of normal training. Each testing session will follow the same format of 6 dives at maximal effort using your preferred stroke with three minutes rest in-between each trial.

During the intervention period you will be given one parameter of the underwater phase to work on. These parameters will be chosen based on previous research. You will then have three Wetplate sessions per week where you will be given specific numerical feedback to assist your start performance improvement. During these sessions you will be asked to perform six maximum effort dives. As an additional requirement of this study you will be asked not to perform any other dives as part of training during this time, as added training by alter the results of the study.

**Potential discomforts and risks**

There are no added discomforts and risks associated with participating in this study as all trials will be incorporated into your training program as specified by your coach.

**Right of Withdrawal**

You should understand that participation in this study is completely voluntary. You can choose to withdraw at any stage or time in the process without any consequence. By signing the informed consent you are indicating that the tests and procedures of this study have been explained to you and understood by you.

**Confidentiality**

All information given by you will be stored on a password protected computer or filed with restricted access at the AIS. All information presented for publication will remain anonymous and reports generated from the analysis of each trial will only be distributed to you and your coach.

This study is being conducted in conjunction with a PhD Project. A report of the study will be submitted as a PhD thesis and presented in scientific publications and at seminars; therefore individual participants will not be identifiable in such a report.

**Enquiries**

If you have any enquires regarding requirements and procedures used in this study or would like further information please do not hesitate to contact the investigators.

| | |
|---|---|
| Elaine Tor | (02) 6214 1915 |
| Dr David Pease | (02) 6214 1732 |

**If you have any concerns with respect to the conduct of this study, you may contact the Secretary of the AIS Ethics Committee (Helene Rushby) 02 6214 1577**.