Identification of Key Performance Variables in Prone and Supine Underwater Dolphin Kick

V M JONES

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Identification of Key Performance Variables in Prone and Supine Underwater Dolphin Kick

Victoria M Jones

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List of Abbreviations

UDK	Underwater dolphin kick
GB	Great Britain
FINA	Federation Internationale De Natation
CFD	Computational fluid dynamics
DLT	Direct linear transform
COM	Centre of mass
ICVV	Intra-cycling velocity variation
V_{COM}	Speed of the centre of mass
V_{REEL}	SpeedReel speed
V_{MIDHIP}	Speed of the mid-point of the hips
RMSE	Root mean squared error
LOA	Limits of agreement
SWC	Smallest worthwhile change
CRP	Continuous relative phase
CRPstart	CRP value at the start of the kick cycle
CRPend	CRP value at the end of the kick cycle
CRPtransition	CRP value at the transition point between knee extension phase and knee flexion phase
CRPext	Mean CRP over the knee extension phase
CRPflex	MeanCRP over the knee flexion phase
SDext	Mean between-cycle standard deviation over the knee extension phase
SDflex	Mean between-cycle standard deviation over the knee flexion phase

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Abstract

In freestyle, backstroke, and butterfly races, swimmers may travel up to 15 m underwater following the dive entry and after the wall push-off in turns. The underwater dolphin kick (UDK), a cyclical movement comprising oscillations of the segments of the lower limb, is customarily used in this underwater phase. It was unknown whether kinematics and coordination patterns differed between UDK performed prone and supine. This thesis contributes to the current body of knowledge on the key performance variables of prone and supine UDK technique, thereby providing practical outcomes for coaches and practitioners to assess and improve UDK. Four studies were conducted to determine: 1) how start and turn performance of Great Britain's (GB) swimmers compare with the rest of the world, 2) if a velocity-meter can be used interchangeably with video-based measurement of UDK speed, 3) if key kinematic metrics differ between prone and supine UDK, and 4) if coordination patterns differ between prone and supine UDK. Relative to clean swimming speeds, GB had slower starts and turns than the rest of the world in some events, but were equal to or faster in other events. Compared to the video-based method, the velocity-meter over- and under-estimated maximum and minimum kick cycle speeds, respectively; mean speeds were similar. With the exception of one upper body metric, no significant differences were found between prone and supine UDK kinematics. Differences were found between sexes, with males demonstrating significantly larger kick amplitude, maximum toe speeds, and distance per kick. Males reached maximum knee separation earlier in the kick cycle, and minimum foot separation later than females. Hip extension velocity, knee flexion velocity, and ankle plantar-flexion velocity were key determinants of UDK performance. Faster kickers maintained horizontal centre of mass speed over the entire underwater phase better than the slower kickers. A temporally sequential movement pattern was found for the knee flexion phase, but not the knee extension phase. Furthermore, coordination patterns between the hip and knee, and knee and ankle, did not differ significantly between prone and supine kicking. This thesis demonstrated that, though individual differences in technique do exist, the kinematics and coordination patterns observed in prone and supine UDK do not differ significantly.

CHAPTER ONE

INTRODUCTION

CHAPTER ONE

Introduction

1.1. Introduction

Swimming has been a leisure activity for centuries, with the Egyptians, Greeks, and Romans participating regularly. However, the United Kingdom was the first modern society to develop swimming as a sport, with the Amateur British Swimming Association formed at the end of the 19th century (Swim England, 2022). With the founding of the modern Olympic Games in 1896, swimming formed part of the competitive programme; only four events were included, and women were not permitted to participate (Marinof and Coumbe-Lilley, 2016). Indeed, women were not able to compete in Olympic swimming until 1912. The formation of the Federation Internationale De Natation (FINA)[1] took place in 1908 during the London Olympic Games of that year (FINA, 2021). This was the first time that the sport was under worldwide governance, and FINA continue to specify and enforce the rules and regulations to which the sport and its athletes are bound.

There are currently 40 official individual swimming events, 32 of which are recognised as Olympic events (Marinof and Coumbe-Lilley, 2016). There are four main strokes by which these events are raced, namely, backstroke, breaststroke, butterfly, and freestyle, alongside the combination of these within the Individual Medley (IM). The FINA rules state that:

> *"Freestyle means that in an event so designated the swimmer may swim any style, except that in individual medley or medley relay events, freestyle means any style other than backstroke, breaststroke or butterfly" (FINA SW 5.1).*

Given that front crawl is the fastest stroke it is the style most often chosen in freestyle events, leading to the two terms becoming effectively synonymous within the

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[1] As of January 2023, FINA is now known as World Aquatics, with all rules and regulations remaining the same under a new name.

swimming environment. In the pool, events in backstroke, butterfly, and breaststroke range from 50 m to 200 m, whilst freestyle events range from 50 m to 1500 m; the IM is swum over 200 m or 400 m. Despite the very first Olympic swimming events taking place in open water in 1896, open water swimming as it is known today (or ‘marathon swimming’) was officially introduced to the Olympic roster at the 2008 Beijing Olympic Games (Swim England, 2022). Open water swimming comprises events over 5 km, 10 km, and 25 km; however, only the 10 km is competed in at the Olympic Games.

Modern swimming events take place in either 50 m or 25 m swimming pools, denoted as long-course and short-course competitions respectively. Competition pools are rigorously controlled and include starting blocks from which to dive and instrumented touch pads at each end that record the turning and finishing times of each athlete. The use of technology in swimming has a long history, ranging from the rapid evolution of training devices to the innovation and reiteration of race suits, caps, and goggles. One of the initial drivers of developing specific suits for competitive swimming was the concern for public decency (Shelton, 2012). When women were eventually permitted to compete in swimming in the Olympic Games in 1912, the suits they wore were made of silk that became semi-transparent when wet. Silk was used until 1957, at which point Speedo launched a suit made of nylon (Speedo, 2022). However, the first iteration of ‘skinsuits’ was used at the 1972 Olympics by East German athletes. These were cut to strictly follow the body shape in an attempt to reduce drag. Following a series of world records broken as a result, the rest of the World also adopted this form of swimwear in 1973. Speedo were again ahead of the curve when they released the ‘Fastskin’ in 2000. These suits were designed to imitate the texture of the skin of sharks to ensure better transfer of water over the swimmer’s body. The suits covered the entire body, between the neck and ankles and wrists. Speedo continued innovation around these suits, providing versions for different strokes, and claiming that they promoted better oxygen flow and a more streamlined position as part of their marketing. Alongside compressing the body, they also trapped a layer of air to improve buoyancy. However, race times were reduced, and records broken to such a large degree that FINA banned their use in 2009, in an attempt to refocus the sport on the physical performance and preparation of athletes. The ban came into effect on January 1st 2010, after 43 new World Records were set at the 2009 World Aquatic

Championships in Rome. As such, marginal gains to ensure success must be found as a result of the athlete's superior technique, physiology, and training.

Within a competitive swimming race, an athlete's aim is to swim the race distance within the shortest time possible, whilst abiding by the rules of the event. Races can be broken down into distinct phases, namely the start, turn, free swim, and finish (Maglischo, 2003). Each of these phases necessitates careful consideration, as an error in any one of them may have a substantial impact upon performance. A swimming start is also often separated into sub-phases: the block phase, flight phase, and underwater phase (Seifert *et al*., 2007). The block phase consists of the time between the starting signal and the athlete's toes leaving the block. The flight phase then comprises the time between the foot leaving the block and the athlete's head entering the water (Tor *et al*., 2015). As these two sub-phases are the only two taking place predominantly above the water surface, athletes should theoretically travel fastest due to less resistance. It is suggested that, in order to maximise benefits obtained from the flight phase, swimmers should aim to increase their entry distance. Flight distance has shown to be a performance determinant within the start (Ruschel et al., 2007), providing it does not cause an increase to entry hole or flatten the trajectory. The underwater phase is defined as the time between when the swimmer's head enters the water and when it resurfaces at breakout (Tor et al., 2015). Equally, the underwater phase within a turn comprises the time between the athlete's feet leaving the wall and when the head resurfaces at breakout. This phase has been established as a significant component of start and turn performance (Cossor and Mason, 2001; Seifert et al., 2007; Tor et al., 2015), as it is when the swimmer will be travelling their fastest through the water. However, it may be prudent to note that each sub-phase influences the next along the chain. Consequently, variations within one sub-phase may cause changes in the next.

During the underwater phase of starts and turns within freestyle, butterfly, and backstroke, swimmers will travel through the water using the underwater dolphin kick (UDK). This method of kicking comprises a cyclical movement involving oscillations of the segments of the lower limb; such oscillations are optimally timed to generate an undulatory wave that travels caudally towards the toes (Atkison et al., 2014; Connaboy et al., 2009). The amplitude of this wave increases at each body segment, systematically transferring momentum along the segments and eventually to the surrounding water, resulting in propulsion (Atkison et al., 2014; McHenry et al., 1995). Alongside the four main strokes already discussed, UDK is frequently referred to as the "fifth competitive stroke" (Collard *et al*., 2013; Phillips *et al*., 2020[a]). This once 'revolutionary' practice has developed over the last 25 years to be a formidable weapon in the swimmer's arsenal if performed well. There is some discourse concerning the official origins of the UDK. It is widely attributed to David Berkoff in the 1980s, with media proclaiming it the 'Berkoff Blast-off' (Collard et al., 2013). Yet its invention could be argued to have taken place as far back as the 1930s. At a time when many swimmers were experimenting with recovering their arms above the surface rather than below as in traditional breaststroke, Volney "Bill" Wilson was exploring how animals propelled themselves through the water (Doezema, 2016). Noting that marine mammals moved their tails up and down rather than side to side like fish, Wilson began attempting a 'dolphin' kick for surface swimming, though continuing to use the traditional breaststroke arm pull simultaneously (Doezema, 2016). However, there is also some speculation that it was initiated by American swimmer Jess Vassallo, when he began including UDK during his starts and turns (Madge, 2014). His rationale for doing so, however, was more concerned with body stabilisation and to avoid wave drag from other swimmers than it was with speed (Madge, 2014). As a result, it gained little traction until Daichi Suzuki incorporated UDK during the 1980s, continuously increasing his underwater distance (Madge, 2014). Regardless of its origins, the advantage of swimming underwater has hardly been emphasised more than during the 1988 Olympic Games in Seoul, when Daichi Suzuki and David Berkoff swam 35-40 metres of the 100 m backstroke race underwater. Berkoff broke the world record during the heat, yet was beaten by Suzuki in the final (Kardjono and Rachmawati; 2019; Marinof and Coumbe-Lilley, 2016). In addition to Berkoff and Suzuki in 1988, Denis Pankratov raced much of the 100 m butterfly underwater, also breaking the world record, at the 1996 Olympic Games. Due to these events, FINA imposed new rules restricting UDK to the first 15 m following the start and each turn; this restriction was first enacted against backstroke following the 1988 Games, then butterfly in 1998, and finally freestyle. Breaststroke has its own set of strict rules governing the underwater phase, but these are beyond the scope of this research.

For freestyle, butterfly, and backstroke, the rules set out by FINA state that:

> *"Some part of the swimmer must break the surface of the water throughout the race, except it shall be permissible for the swimmer to be completely submerged during the turn and for a distance of not more than 15 metres after the start and each turn. By that point, the head must have broken the surface." (FINA SW5.3 and SW6.3).*

The main advantage of swimming below the surface is thought to be a reduction in wave drag, thereby improving propulsive efficiency (Lyttle et al., 1998). Additionally, the friction that the athlete encounters from swimming through one medium (water) is reduced compared to that when swimming through two different media and thereby encountering the air-water interface (Kardjono and Rachmawati, 2016). Consequently, although the distance over which an athlete may swim underwater is restricted, it is advantageous to ensure they swim as much of the 15 m underwater as possible. As start and turn times can account for up to 26.1% of final race time, depending on the event (Cossor and Mason, 2001), improvements in underwater kicking technique could have a significant impact on performance.

Following the Rio 2016 Olympic cycle, a research group was created amongst British Swimming and its partners, dedicated to the principles and application of drag reduction. This group comprises experts from British Swimming, British Para-Swimming, the English Institute of Sport, TotalSIM, Manchester Metropolitan University, and the University of Southampton. At the beginning of the Tokyo Olympic cycle, i.e., 2016-2017, it was agreed within this group that starts and turns were areas that required additional focus and resources within the upcoming cycle for the British team. Funding was subsequently made available for PhD projects, one of which is the current body of work. Cognisant to the fact that the underwater phase can account for a significant amount of start and turn time (Slawson *et al*., 2013), it was thereafter decided that UDK in the underwater phase of starts and turns would constitute the predominant focus.

1.2 Thesis Aims and Objectives

The global aims of the thesis are to:

1) contribute to the current body of knowledge on the key performance variables of prone and supine UDK technique;

2) provide practical outcomes for coaches and practitioners to assess and improve UDK.

The specific thesis objectives are to:

1) Determine how start and turn performance differs between top-performing GB athletes and medallists from the rest of the world. This objective will be addressed in Chapter Four;
2) Assess the agreement in instantaneous speed measures from a velocity-meter compared with a video-derived criterion measure. This objective will be addressed in Chapter Five;
3) Establish whether kinematic differences exist between prone and supine UDK and between males and females. This objective will be addressed in Chapter Six;
4) Determine if movement patterns in maximum effort UDK demonstrate a temporal sequence in both phases of the kick cycle. This objective will be addressed in Chapter Seven;
5) Determine whether differences exist in coordination patterns in prone and supine UDK, between males and females. This objective will be addressed in Chapter Seven.

1.3 Structure of thesis

This thesis comprises a review of the current literature on UDK followed by four experimental studies. Finally, there is a chapter on general conclusions and future recommendations.

Chapter Two contains the literature review, which summarises and identifies gaps in the body of knowledge on UDK.

Chapter Three is a General Methods chapter, detailing those elements of data collection and processing that were common amongst multiple studies in this body of work.

Chapter Four examines how the start and turn performance of Great Britain’s swimmers compares with that of medallists from the rest of the world. Start and turn times to 15 m, alongside clean swim speeds, were correlated with final race time.

Chapter Five comprises a methodological comparison between a criterion method of measurement (three-dimensional video analysis) and a velocity-meter system commonly employed within the high-performance training environment (SpeedReel). This study assessed the agreement between the two methods, and subsequently provided guidelines for future users of the SpeedReel to facilitate appropriate use in a practical setting. If it were found that the two methods could be used interchangeably, the SpeedReel could have been used throughout the remainder of the thesis. However, it was concluded that they should not be used interchangeably; consequently, the SpeedReel was not used in the subsequent studies.

Chapter Six details three-dimensional kinematic and temporal parameters of elite UDK, and compares UDK performance of males and females, performed prone and supine. This chapter also presents a novel kick-by-kick analysis of these metrics over the underwater phase.

Chapter Seven presents an exploration of coordination patterns within elite UDK performance, beginning with a temporal analysis of the segments of the trunk and lower limb. This is followed by qualitative evaluation via angle-angle plots, and quantitative assessment via continuous relative phase.

Chapter Eight comprises a summary of findings, practical implications, limitations, and recommendations for future research.

CHAPTER TWO

LITERATURE REVIEW

CHAPTER TWO

Literature Review

2.1 Introduction

The research surrounding underwater dolphin kick (UDK) is extensive and encompasses a multitude of topics, some of which are beyond the scope of this thesis. Consequently, this chapter aims to synthesise, review, and appraise the relevant body of knowledge with particular focus on those factors considered to be determinants of performance. As such, this chapter aims to review the current understanding of UDK performance with respect to the following areas:

- Comparison of undulatory swimming mechanisms between marine mammals and humans
- Kinematic parameters
- Hydrodynamics
- Coordination and motor control

In doing so, this chapter aims to identify gaps in the extant knowledge base, and indicate what is required in terms of future research.

2.2 Undulatory underwater swimming among marine mammals and humans.

Compared to the naturally adept swimming technique of marine mammals, human undulatory underwater swimming is relatively slower and less efficient (Connaboy *et al.*, 2009). There are many factors that impact undulatory locomotion including morphology, the degree of body flexibility or rigidity, and the amplitude and frequency of the end-effector, e.g., the feet in human swimming (Hochstein and Blickhan, 2014). Due to the existence of variations across different species, these factors have been used to categorise certain types or modes of undulatory locomotion, based predominantly on the waveform propagation and the amplitude of the body movements (Connaboy *et al.*, 2007). Based upon these classifications, human underwater undulatory swimming has been categorised as sub-carangiform (Connaboy *et al.*, 2007). This is because it involves less than one wavelength per body length, and most of the body participates in the waveform, yet it is predominantly the distal aspects that generate the propulsion (Connaboy *et al.*, 2007; Ungerechts *et al.*, 1998). Further, one of the main sources of inefficiency as a result of undulatory locomotion is inertial recoil, that is, heaving or lateral motions of the more proximal aspects of the body due to large oscillations of the tail or lower limbs (Webb, 1992). This can bring the body out of streamline, increase form drag, and compromise the generation of propulsion (Connaboy *et al*., 2007; 2009). It has been suggested that, within humans, the extended arms act as a dampener to minimise these effects; instead of contributing directly to propulsion, the trunk absorbs the recoil from the lower limbs (Connaboy *et al*., 2009; Nakashima, 2009).

Marine mammals and humans propel themselves through the water by transferring momentum to the surrounding fluid (Ungerechts *et al*., 1998). Dolphins will rapidly oscillate their tail and flukes, as a result of the large degree of freedom provided by a double joint between the fluke and peduncle (Ungerechts *et al*., 1998). In contrast, human swimming is described as a more undulating movement dictated by the anatomical constraints within the lower limb; the presence of only three rotational joints in the lower limb means that more of the body must be used in order to create a body wave (von Loebbecke *et al*., 2009a; Ungerechts *et al*., 1998). The body wave describes the propulsive waveform that is initiated towards the upper body and progressively increases in amplitude caudally (von Loebbecke *et al*., 2009[a]). In contrast, dolphins and other cetaceans will instead restrain the displacement along the length of the body until it reaches the peduncle, where it will increase abruptly (von Loebbecke *et al*., 2009a); the fluke will then oscillate like a whip, thus resulting in a rotation of water known as a vortex (Ungerechts *et al*., 1998). These rotating masses of water are purported to be integral to effective propulsion within undulatory locomotion (Arellano, 1999; Connaboy *et al*., 2009; Hochstein and Blickhan, 2011; von Lobbecke *et al*., 2009b).

Descriptions of the movements involved in UDK originated via the comparison of human motion to that of dolphins. The aforementioned discrepancy between the movement of the dolphin and of the human swimmer is thought to be due to morphological and flexibility restrictions within the ankles and feet (von Loebbecke *et al*., 2009a; Ungerechts *et al*., 1998). Humans have therefore been advised to utilise as fast a change of direction as possible whilst kicking, by using a whip-like motion with the lower limbs (Ungerechts *et al*., 1998); this is purported to emulate the movements of the fluke, and thus generate the propulsive changes in fluid flow that result. It is suggested that the culmination of the upbeat of the fluke creates a vortex carrying rotational momentum; this is then destroyed by a torque generated during the downbeat, resulting in the release of stored momentum and, consequently, forward propulsion (Ahlborn *et al*., 1991; Ungerechts *et al*., 1998). However, it is important to note that dolphins' swimming motion has been categorised as thunniform, whereas human UUS is sub-carangiform (Connaboy *et al*., 2007). As such, there are many differences in how each species propels themselves through the water, including the length of the waveform and the presence or absence of oscillations/undulations over the whole body, rather than just the caudal aspects (Connaboy *et al*., 2007). As these two modes of undulatory locomotion are at different ends of the spectrum, direct comparisons and subsequent recommendations must be made cautiously, if at all.

Many authors have nevertheless postulated that the same hydrodynamic mechanisms can be used to explain both human and marine mammal underwater locomotion (Arellano, *et al*., 2002; Connaboy *et al.,* 2009; Sanders *et al*., 1995; Ungerechts, 1983). A primary investigation into the comparison between species maintained that the models used at the time to describe hydromechanics of human competitive swimming focused solely on resistive forces (Ungerechts, 1983). Consequently, the reaction forces that arise due to transferring momentum to the surrounding water were being neglected; this is important as both are integral to understanding locomotion through water. It has been suggested that it is difficult to derive separate drag and propulsive components from external forces because both aspects occur in synchronicity (Ungerechts *et al*., 1998). Moreover, unlike a rigid body, a swimmer's body is continuously moving and changing shape, resulting in unsteady flow conditions and affecting the rate of momentum transfer at different phases of a stroke cycle (Ungerechts *et al*., 1998). Ungerechts (1983) thus sought to identify similarities between movements of humans and cetaceans, so as to be able to apply the reactive model to human competitive swimming.

After completing kinematic comparisons of six dolphins and seven world class butterfly swimmers, analyses were conducted on the velocity that the body wave travelled caudally along the body (body wave velocity), and durations of the upkick and downkick (see Figure 2.1 for illustration of these phases) (Ungerechts, 1983).

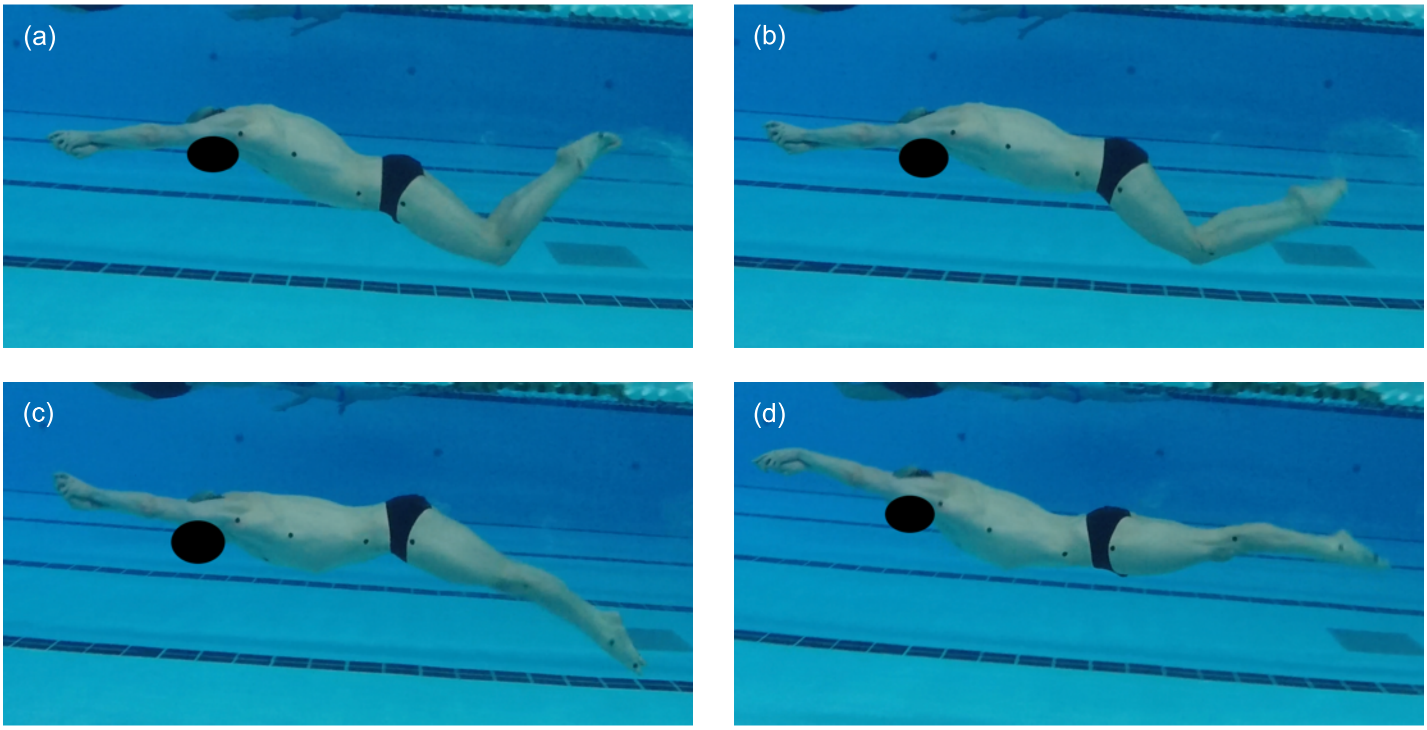


Figure 2.1: Photo-sequence demonstrating the two kick phases: (a) and (b) downkick, (c) and (d) upkick.

Body wave velocities appeared to be statistically similar, yet the dolphins had a more symmetrical amplitude between upbeat and downbeat, thought to be due to the greater flexibility provided by the fluke than that of the humans' lower limb (Ungerechts, 1983). However, whilst there was no statistically significant difference in duration of upbeat and downbeat for the swimmers, there was a difference for the dolphins; the upbeat was performed more quickly than the downbeat (Ungerechts, 1983). Additionally, this study examined the kinematics of the butterfly stroke on the surface, rather than fully-submerged UDK. Consequently, the movement patterns will differ somewhat, both due to the addition of the arm-stroke with full butterfly, and the differences in drag that occur at the surface compared with full immersion.

2.3 Kinematics

Of the many kinematic variables investigated within UDK, kick frequency is one of the most studied (Alves *et al*, 2006; Arellano *et al*., 1999; Atkison *et al*., 2014; Connaboy *et al*., 2016; Gavilan *et al*., 2006; Hochstein and Blickhan, 2014; Houel *et al*., 2013; Ikeda *et al*., 2021; Shimojo *et al*., 2014, 2019; von Loebbecke *et al*., 2009[b]; Wadrzyk *et al*., 2019; Willems *et al*., 2014). A reason for it being of such interest may be that, in marine mammals, the association between end-effector frequency and forward swimming velocity is linear (Webb *et al.*, 1984). Additionally, it forms one element of the relationship that determines UDK speed, i.e., rate (frequency) and length (distance per kick) (Connaboy *et al.*, 2016). However, despite the assertion of a linear relationship within marine mammals, the same cannot necessarily be applied to human UDK. Indeed, it has been suggested that there is a preferred or optimum kick frequency for a given swimmer, and that to increase the frequency above that does not provide further performance benefits, but may in fact be detrimental (Shimojo *et al.*, 2014; Yamakawa *et al.*, 2017). With increasing frequencies above the swimmers' preferred frequency, swimming velocity did not change (Shimojo *et al.*, 2014). However, kicking amplitude and distance per kick were reduced, alongside propelling efficiency (Shimojo *et al.*, 2014), defined as 'the fraction of [total mechanical power] that can be utilised to overcome external forces in water' (Gatta *et al.*, 2018:506). The combination of increased energy expenditure resulting from increasing frequency above that which is preferred, and a concomitant reduction in kick amplitude and distance per kick, is evidently disadvantageous. Further, several authors have found no correlation between swimming speed and kick frequency when examining the relationship between swimmers (Atkison *et al.*, 2014; von Loebbecke *et al.*, 2009[b]). However, this does not necessarily denote a lack of importance for kick frequency in impacting UDK; it may simply be that kick frequency is an individual preference based upon skill level, sex, limb length, height, and other morphological characteristics.

Mean swimming velocity or speed (UDK speed) provides the main performance measure for much of the literature regarding UDK. This is unsurprising given the aim of a swimming race is to cover the race distance in the shortest time possible; therefore, when considering which variables are key to improving performance, it is logical to consider them with respect to how they relate to swimming speed. However, there exist discrepancies in how UDK swimming speed is calculated and defined. The majority of authors calculate the centre of mass speed or horizontal velocity (Atkison *et al.*, 2014; Gavillan *et al.*, 2006; Higgs *et al.*, 2017; Matsuuda *et al.*, 2021; Shimojo *et al.*, 2014; Taneka *et al.*, 2020; Wadrzyk *et al.*, 2019). Others report either the horizontal velocity of the hip (Hochstein and Blickhan, 2011, 2014; Ikeda *et al.*, 2021) or of the midpoint of the two hips (Yamakawa *et al.*, 2018). Whilst it is often purported that these points are synonymous with, or provide a valid proxy for, the centre of mass (Hochstein and Blickhan, 2011, 2014), direct comparisons may not always be accurate as the hip is a fixed point on the body, whereas the location of the centre of mass can change and will not always move synchronously with the hips. Root mean square error values have been found to range between 0.16 m.s^{-1} and 0.30 m.s^{-1} for the velocity of the hip compared with the velocity of the centre of mass (Figueiredo *et al*., 2009).

A wide range of swimming or kicking velocities are reported within the literature, in part due to the skill level across samples. Arellano *et al*. (2002) compared the velocity of the centre of mass and hip, alongside the horizontal component of these velocities, between a national level group (seven males and six females) and an international level group (12 males and seven females) performing UDK. Predictably, velocities were higher in the international group than the national (1.61 m.s^{-1} and 1.15 m.s^{-1} for the centre of mass respectively). Even within sample groups, differing skill levels can produce a wide range of velocities; a study in which participants' FINA points varied from 445 to 868 found centre of mass velocities between 1.84 m.s^{-1} and 1.30 m.s^{-1} (Atkison *et al*., 2014). An even more pronounced difference was observed in an earlier investigation that comprised nine female and 13 male Olympic level athletes performing UDK, with a similar highest velocity reported, yet the slowest swimmer was 1.12 m.s^{-1} (von Loebbecke *et al*., 2009[b]). These discrepancies highlight that, even within a supposedly skilled cohort, swimming velocities can vary substantially; elite swimmers are not necessarily elite kickers.

Vertical toe velocity has been found to be a key predictor of UDK performance (as denoted by horizontal centre of mass velocity) (Atkison *et al*., 2014; Higgs *et al*., 2017). In order to ensure fast movement through the water, it is considered necessary to ensure a high end-point speed (in this context, the toe) achieved via a proximal-to-distal sequencing of segments to result in cephalo-caudal momentum transfer (Higgs *et al*., 2017; Hochstein and Blickhan, 2011, 2014; Lees, 2008). In this way, the velocity of each segment must be higher than the preceding segment, and thus the foot (and, ultimately, the toe) must be travelling the fastest, so as to produce powerful vortices contributing to the generation of thrust (Arellano, 1999; Ungerechts *et al*., 2000). However, it has been purported that optimum UDK performance relies on both a high vertical toe velocity and body wave velocity, defined as the speed of "caudal momentum transfer" (Higgs *et al*., 2017). Precisely timed displacements of the required segments result in a wave that travels down the body towards the toes (Gavilan *et al*., 2006). In this way, the motion of UDK is considered to be sinusoidal.

This wave has been found to differ based upon the skill level of the participants involved, with skilled swimmers demonstrating smaller relative segment amplitudes along the course of the body than less skilled swimmers (Hochstein and Blickhan, 2014).

A variety of definitions for kick amplitude has been used within the literature, from the peak-to-peak toe amplitude (i.e., the difference between the maximum and minimum vertical displacements of the toe) (von Loebbecke *et al*., 2009[b]), to the mean peak-to-peak amplitude of the ankle (Houel *et al*., 2013), to the average vertical displacement of the toe (Atkison *et al*., 2014). As with average swimming velocity, the lack of consensus on a standard definition of kick amplitude makes comparison between studies difficult. Amplitude was not found to correlate with mean centre of mass velocity in a study of 10 (seven male and three female) freestyle, backstroke, and butterfly athletes by Higgs *et al*. (2017); however, in another study (in which no gender nor specialism of athletes was detailed), amplitude was found to be one of the best predictors of horizontal velocity (Houel *et al*., 2013). The discrepancy between these two studies may be due to differences in methodology; for example, the definition of kick amplitude differed between the two, with Higgs *et al*. (2017) using the maximum vertical displacement of the toe, while Houel *et al*. (2013) used the mean peak to peak amplitude of the ankle. Additionally, the participants in the former study began each trial from a wall push-off, whereas Houel *et al*.'s (2013) participants began from a grab start off the blocks. Regardless, it appears that there is not yet a consensus on the importance of kick amplitude on swimming velocity. Nevertheless, a reciprocal relationship is apparent between kick frequency and kick amplitude (von Loebbecke *et al*., 2009[b]). This relationship may be manipulated to identify the optimum ratio for individual swimmers, as the relationship between end-effector amplitude and forward swimming velocity has been suggested to be independent (Connaboy *et al*., 2009). As such, instead of one optimum amplitude, this parameter may be individual to each athlete, based upon their own organismic constraints (e.g., height and limb length) and task constraints (i.e., race distance and event).

Alongside kick amplitude, some authors have investigated other joint amplitudes within the lower limb or entire body. Transverse amplitudes of four lower body and five upper body joints or segments were described in three different kicking orientations, prone, supine, and lateral (Alves *et al*., 2006). Across all three orientations, amplitudes of the upper body were smaller than those of the lower limb, which increased caudally. Further, joint amplitudes were largest in lateral kicking, followed by supine, and then prone; centre of mass amplitudes, for example, were 0.08 m, 0.05 m, and 0.03 m respectively (Alves *et al*., 2006). However, no explanation for the disparities in amplitude between kicking modes was provided; thus, differences in technique between kicking modes have not been conclusively established. Additionally, joint amplitudes have been found to increase quadratically from the hand to the toe (Hochstein and Blickhan, 2014). The purpose of this progression is likely to ensure the required proximal-to-distal sequence required for correct momentum transfer. It has also been shown, however, that the amplitudes along the body are vertically asymmetric with respect to the midline, that is, above and below the centre of the streamlined body position (Hochstein and Blickhan, 2014). However, it was demonstrated that the feet move nearly symmetrically, and was suggested that skilled swimmers coordinate their segments so as to ensure near symmetry of the end-effector (Hochstein and Blickhan, 2014). It remains unclear, however, exactly how this is achieved.

Alongside relatively simple measures such as kick frequency and amplitude, the importance of higher-order metrics such as joint angles and angular velocities has also been investigated. The horizontal velocity of the greater trochanter, a measure of UDK performance, was found to significantly correlate with lower trunk angle in both kick phases, alongside peak angular velocity of the upper leg (Ikeda *et al*., 2021). Additionally, the absolute segment angles of the trunk and lower leg were found to differ considerably between faster and slower male freestyle and butterfly swimmers in that same study (Ikeda *et al*., 2021). However, no other significant correlations were found between angular variables and UDK performance. Conversely, when using the centre of mass velocity, significant correlations were found between UDK speed and peak angular velocities of the external and internal rotation of the hip (r = -.74, p = <.01, and r = .48, p = .01, respectively), peak knee flexion angular velocity (r = -.45, p = .02), and peak ankle plantarflexion velocity (r = -.40, p = .04) (Matsuda *et al*., 2021). Additionally, the mean angular velocities of the lower waist and chest were found to be significantly correlated with the horizontal velocity of the centre of mass (r = .70, p = <.02, and r = .73, p = .02, respectively) (Tanaka *et al*., 2020). The contrasting findings between these studies may be due to differences in the performance measure; further, the skill level of each cohort differs, with FINA points ranging from 600 to 920. As such, the relationship between joint angles and angular velocities, and forward swimming velocity is not yet conclusive; to do so may require a standardisation in the performance measure with which these possibly crucial kinematic variables are compared.

Though skill level and technique are undoubtedly crucial to proficient UDK, improvements in physical and morphological aspects may also enhance performance. Flexibility in the knees and ankles is considered to be instrumental in ensuring the ‘whip-like’ kick required for thrust production (Atkison *et al*., 2014; Gavilan *et al*., 2006), with those swimmers able to hyperextend the knees and ankles often faster than those who cannot. The effect of ankle flexibility and muscle strength on UDK performance has been evaluated by Willems *et al*. (2014). Significant, positive correlations were found between UDK speed and the strength of the ankle dorsal flexors (r_s = .53, p = .006) and internal rotators (r_s = .47, p = .02). Furthermore, restricting the ankle range with tape (15% active and 22% passive restriction of internal rotation, 30% active and 29.5% passive restriction of plantar flexion) effected a reduction in swimming velocity; the authors posited that, following taping, movement patterns changed to rely more on knee flexion in the absence of plantar- and dorsi-flexion (Willems *et al*., 2014). However, neither active nor passive range of ankle motion correlated with UDK velocity (Matsuda *et al*., 2020; Willems *et al*., 2014), perhaps indicating that muscle strength, rather than range of motion, is more important to UDK. It could be inferred that, to improve UDK performance, athletes and coaches should focus on active mobility rather than merely passive flexibility of the ankles.

With respect to the knee, range of movement of the knee during UDK was one of three variables to explain most of the variance in maximal UDK speed in a study of eight male and nine female age-group swimmers (Connaboy *et al*., 2016). However, within this study, participant was included as a fixed factor to allow for individual differences; when this was removed, the only significant covariate remaining was maximum knee angular velocity (Connaboy *et al*., 2016), the direction of which was not stated. It was concluded that the reduction in explained variance was due to individual movement solutions dictated by various organismic constraints (Connaboy *et al*., 2016). The results may also be due to the participant sample; different results may be obtained with higher level and more mature swimmers than the age-group, national-level cohort used.

Though marine mammals vertically undulate symmetrically in both directions, humans are anatomically restricted by means of less flexibility and a smaller end-effector (Atkison *et* al., 2014). A comparatively smaller number of joints and range of motion within those joints means that the capacity for a continuous production of thrust is limited for human swimmers (von Loebbecke *et al.*, 2009[b]). Nevertheless, it remains important to maximise kick symmetry where possible, defined as “the ability to produce equivalent propulsion during the downkick and upkick phases” (Atkison *et al.*, 2014:299). This will ensure two propulsive phases of the kick, rather than allowing the second to be mostly resistive (Atkison *et al.*, 2014). In investigating the relationship between kick symmetry and performance in fifteen male swimmers of varying skill level, symmetry was evaluated via an array of kinematic variables including joint angles, kicking amplitude and frequency, and vertical toe velocities (Atkison *et al.*, 2014). Ensuring maximum vertical toe velocities in both kick phases resulted in a higher UDK speed for the fast swimmers, thereby generating similar propulsion throughout both phases of the kick (Atkison *et al.*, 2014). Additionally, the relative amount of time spent in the downkick and upkick has been proposed as a critical indicator of skilled UDK performance (Atkison *et al.*, 2014; Higgs *et al.*, 2017). Faster swimmers divide the kick cycle time evenly between phases, whereas slower swimmers spent comparatively longer in the upkick phase (Atkison *et al.*, 2014). This could be particularly disadvantageous if the upkick is a predominantly resistive phase for an athlete; less time for propulsion and more time experiencing drag over each kick cycle will inevitably reduce a swimmer’s speed over their underwater phase. The authors concluded that flexibility in the upper thoracic spine, knees, and ankles is important for successful UDK, alongside recommending limiting the duration of the upkick and ensuring high maximum toe velocities during this phase.

Though the majority of the research on UDK has been completed with the swimmers prone, UDK is also used to great effect in backstroke starts and turns, during which swimmers perform the UDK supine. Despite this, only two studies compare UDK in more than one kicking orientation (Alves *et al.*, 2006; Arellano *et al.*, 1999). In a comparison of prone, supine, and lateral kicking, no significant differences were found between prone and supine UDK for mean swimming velocity, kick frequency, or vertical joint amplitudes (Alves *et al,* 2006). Differences were found between prone and lateral, with UDK speeds tending to be lower for the lateral kicking (1.27 m.s^{-1}, compared with 1.46 m.s^{-1} for prone, and 1.42 m.s^{-1} for supine). This may reflect the swimmers' lack of familiarisation with the task. Additionally, the participants were junior national-level swimmers; it is unclear if and how UDK performance differs based upon kicking orientation with elite senior athletes. Notably, the degree of body oscillation and angle of attack of the trunk were found to differ significantly in supine kicking compared to prone (Arellano *et al*., 1999). As so few investigations have been completed on kicking orientation, no true consensus has been reached and it remains an area that requires further study.

2.4 Hydrodynamics

A body will move through water by transferring momentum to the surrounding fluid, with the amount of thrust (propulsion) generated determined by the rate of this transfer of momentum (Ungerechts, 1998). The method by which a swimmer propels themselves through water has been the subject of much debate, with the traditional view based upon Newton's third law of motion. It was considered that propulsive force was solely an equal and opposite force to that of resistive drag, termed drag propulsion or hydrodynamic reaction force (Grimshaw *et al*., 2006; Vorontsov and Rumyantsev, 2000). However, in order to continuously move through the water effectively, it is optimal to continuously find and push against immobile water, as this is the stable base with which swimmers propel themselves along (Vorontsov and Rumyantsev, 2000). This is best achieved when the hand and arm move through a more curvilinear path, in contrast to the traditional view that the arm should move straight backwards like an oar (Vorontsov and Rumyantsev, 2000). Subsequently, due in part to the work of Counsilman (1969), it was purported that lift also plays a role in propulsion via the hydrodynamic lift force. The hydrodynamic lift force is the normal component of the hydrodynamic reaction force, and so acts perpendicularly to the direction of the flow of the fluid. As such, it is now widely-considered that both drag and lift contribute to propulsion. The proportion of either component at any given time is dependent upon many factors, including the individual swimmer, the stroke and event, and the phases of that stroke (Vorontsov and Rumyantsev, 2000).

An additional method of propulsion has been proposed, and is instrumental in undulatory locomotion, of which UDK is an example. When a body undulates through the water, the oscillating movements that culminate in pitching movements of the end-effector (the feet in human UDK) result in a rotating mass of water called a vortex (Connaboy *et al.*, 2009). Vorticity is a key element to producing thrust during undulatory movement. As a result of their specific topology, vortices are optimally suited to generate propulsion (von Loebbecke *et al.*, 2009b). A vortex ring produced in a fluid will move as a result of self-induction and cause a powerful directed jet and, therefore, thrust (von Loebbecke *et al.*, 2009b). Such a vortex ring has been observed in the wake structure at the end of the downkick, and for skilled swimmers is directed backwards and downwards (Hochstein and Blickhan, 2011), thereby propelling the swimmer forwards according to Newton’s third law. Several vortices are generated along the body length during underwater kicking, and are primarily shed in regions of high angular acceleration at the joints (Hochstein and Blickhan, 2011). A large vortex is created at the end of the downbeat, and, in the case of more skilled swimmers, a smaller vortex at the end of the upbeat (Arellano, 1999; Arellano *et al.*, 2002); these have been observed via the injection of bubbles, and using particle image velocimetry. Furthermore, the most effective wake structure for improving the efficacy of UDK performance includes two counter-rotating vortices that are shed from the feet into the wake behind the swimmer (Triantafyllou *et al.*, 2002). The jet flow that results as a consequence will enhance the propulsive impulse of the swimmer, if they can adequately control and capitalise on the favourable pressure gradients (Triantafyllou and Triantafyllou, 1995). As such, effective coordination is considered an important aspect for optimal UDK performance. However, it is important to note that this research concerning jet flow was conducted on the movement of fish, and not on humans. Whilst vortices have been observed in the wake of human swimmers, it has yet to be conclusively demonstrated exactly how humans can use vortices to their advantage.

Another aspect of propulsion considered key to undulatory locomotion is the ‘pump effect’ or suction effect (Collard *et al.*, 2008). This describes the effect of accelerating masses of water backwards along the body. During self-propulsion in unsteady flows, which occur when a body oscillates or undulates within a fluid, a body is said to acquire “virtual added mass”, which is purported to result in a phenomenon known as an acceleration reaction force (Ungerechts, 1998; Scaradozzi *et al.*, 2017) or “added mass effect”. When moving through a fluid, work must be done both to increase the kinetic energy of both the body and the surrounding fluid. This results in an added mass and corresponding acceleration reaction force. Like drag, this force acts to oppose motion, however, unlike drag, it resists both acceleration and deceleration (Daniel, 1984). Within the context of human UDK, in order to use this effect, the swimmer must be both fully immersed in the water and travelling at sufficient speed to allow the fluid to flow along the body (Collard *et al*., 2008). Both such conditions occur during a start or turn, and it is suggested that both the pump effect and vortices have an effect on the generation of propulsive lift forces (Collard *et al*., 2008).

The objectives in the literature regarding the hydrodynamics of human UDK include attempting to describe the vortices present in the fluid flow around the swimmer (Arellano, 1999; Colman *et al*., 1999; von Loebbecke *et al*., 2009[c]), and assessments of propulsive efficiency and thrust (Phillips *et al*., 2020 [a] and [b]; von Loebbecke *et al*., 2009 [a]). Vortices have been visualised via bubbles injected into the flow, with a large vortex noted at the end of the downkick (in prone) for all swimmers, but a smaller vortex at the end of the upkick for the fast swimmers only (Arellano, 1999). In a computational fluid dynamics (CFD) study, propulsive efficiencies based upon kinematics of one male and one female Olympic-level swimmer were found to range between 11% and 29%, far lower than the 56% reported for cetaceans (von Loebbecke *et al*., 2009[a]). This was suggested to be due to the greater surface area of a dolphin's fluke compared with the feet of human swimmers enabling a higher thrust production, alongside a smoother body wave due to a greater number of joints available to the dolphin. Regardless, the authors concluded that propulsive efficiency in humans is impacted more by overall style of swimming rather than of any one kinematic metric (von Loebbecke *et al*., 2009[a]).

In an attempt to describe the wake behind the swimmer and how thrust is produced in UDK, von Loebbecke *et al*. (2009[c]) observed a three-dimensional vortex ring within the wake, that was shed at the end of the downkick. In agreement with Arellano (1999), much smaller vorticies that disappeared quickly were observed at the end of the upkick (von Loebbecke *et al*., 2009[c]). It was suggested that the thrust in UDK is produced mostly by the feet, possibly in part because the majority of the vortices created by UDK are shed from areas below the knee (von Loebbecke *et al*., 2009[c]). This finding corroborates an earlier simulation study that also found the thrust is mostly generate by the feet (Sugimoto *et al*., 2008). It was also observed that the downkick produces more thrust than the upkick, and that this disproportion is due to the inherent asymmetry in joint mobility between the front and back of the body (von Loebbecke *et al*., 2009[c]). Additionally, with these swimmers, the majority of the active drag was produced by the chest, hips, and abdomen (von Loebbecke *et al*., 2009[c]). The use of CFD has also been implemented to determine the effect of variations in UDK technique (i.e., changing amplitude and/or frequency) on propulsive efficiency (Phillips *et al*., 2020[a]), and what might be best for different race distances (Phillips *et al*., 2020[b]). A lower frequency kick with more undulation from more segments in the body is suggested to be better for endurance, whereas a high frequency knee-dominant kick may be better for sprint distances (Phillips *et al*., 2020[b]). However, the conclusions drawn from this latter study were based upon one male backstroker, thus may be difficult to generalise to wider populations.

More recently, CFD has been used to investigate the effect that different trunk segmental movements have on the hydrodynamics of UDK (Chen *et al*., 2022). Alongside a positive correlation between trunk movement and mean swimming velocity, it was concluded that larger trunk oscillations led to the production of larger vortices and more thrust from the feet (Chen *et al*., 2022). Furthermore, the upper waist is likely a key segment of the trunk in propagating the body wave caudally (Chen *et al*., 2022). The movement of the trunk has previously been shown to contribute favourably to UDK performance (Nakashima, 2009; Cohen *et al*., 2011). The trunk and the upper body are thought to absorb inertial recoil from the constant oscillations of the lower limb (Nakashima, 2009). Though it does not directly contribute to thrust generation, the trunk is considered to be important for propulsive efficiency, as it helps align the upper limbs in the correct direction (Nakashima, 2009). Whilst the discussed studies provide valuable insight into how internal and external forces might interact with an athlete, the simulated results require experiential corroboration to accurately apply to a wider population.

2.5 Coordination

Coordination may be defined as the generation of appropriate spatial and temporal relations among movement-related events in order to successfully achieve a specific goal (Walter *et al*., 1997). In other words, effectively organising the various movements of the body so as to complete a desired action. This is critical in UDK, due to its high level of technical complexity (Gavilan *et al*., 2006) and is most successfully achieved via proximal-to-distal sequencing (Hochstein and Blickhan, 2014). It has been suggested that UDK is underpinned by a temporal sequence of efficiently coordinated segmental oscillations, such that a ‘body wave’ is generated that travels caudally (Connaboy *et al*., 2009; Gavilan *et al*., 2006). As such, the way in which these oscillations are produced, and their timing with respect to one another, are fundamental in determining the shape and velocity of the waveform (Connaboy *et al*., 2009).

There exists a multitude of methods of assessing and describing coordination, both qualitative and quantitative in nature. For example, angle-angle plots present data on the change in one joint angle with respect to another, thereby enabling a qualitative analysis of coordination patterns between those joints. In order to then obtain quantitative information, a quantitative analysis is required. Using the angle-angle plots, this can be undertaken by use of vector coding (Hamill *et al*., 2000). Alternatively, and incorporating angular velocity data into the analysis, continuous relative phase can be calculated as the phase difference between two oscillating segments over time (Wheat and Glazier, 2006). Cross-correlation functions also present an alternative method for quantifying inter-joint coordination (Lamb and Bartlett, 2017). Indeed, cross-correlations have previously been used to assess coordination in UDK (Elipot *et al*., 2016). However, no significant correlations were found between UDK speed and the joint angles or accelerations investigated, and it was concluded that cross-correlations may not be the most effective method by which to understand coordination in UDK (Elipot *et al*., 2016).

2.5.1 Vector Coding

Vector coding has evolved over time to encompass a range of techniques, all with the underlying principle of quantifying relative motion by investigating patterns in time-evolving systems (Hamill *et al*., 2000; Zehr *et al*., 2018). It originated with work from Freeman (1961) that demonstrated a ‘chain-encoding’ method to quantify an angle-angle curve (Wheat and Glazier, 2006). In brief, a grid is superimposed onto a curve, thus allowing a chain to be created of digits that are based upon the directions of the line segments formed by connecting adjoining grid intersects (Wheat and Glazier, 2006; Whiting and Zernicke, 1982). Subsequently, chains from two different movement cycles may then be cross-correlated (Freeman, 1961; Whiting and Zernicke, 1982). Despite the fact that this form of technique has been used by a few authors to investigate locomotion (Hershler and Milner, 1980; Whiting and Zernicke, 1982), the resulting data are unavoidably in the nominal scale, thus restricting statistical analysis, and possibly incurring a loss of information (Tepavac and Field-Fote, 2001). Additionally, data points must be evenly spaced, an aspect not always guaranteed with human movement data (Sparrow *et al.*, 1987). Consequently, updates or modifications were clearly required of the current chain-encoding method. Vector coding has continued to develop, with modifications being developed as recently as 2015 (Needham *et al.*, 2015). For further information, readers are directed to the extensive review provided by Wheat and Glazier (2006).

With the modified technique presented by Tepevac and Field-Fote (2001), it was possible to analyse an angle-angle plot by its shape via angles, its magnitude via the lengths of the frame-to-frame intervals, or the frame-to-frame vector deviation (a combination of shape and magnitude) (Tepevac and Field-Fote, 2001). This enables a true and appropriate quantitative analysis of an angle-angle plot. However, a further small change to the technique was suggested and utilised by Hamill *et al.* (2000) and Heiderscheit *et al.* (2002). These authors proposed a ‘coupling angle’, and defined it as the orientation of the vector between two adjacent points on the angle-angle plot relative to the right horizontal. This idea of the coupling angle was taken one step further by Chang *et al.* (2008), who suggested that four distinct coordination patterns can be identified based upon the magnitudes of the coupling angles. Their work was concerning gait, and they proposed that the coordinative patterns between the rearfoot segment and the forefoot segment can be summarised as: anti-phase; in-phase; rearfoot phase; and forefoot phase (Chang *et al.*, 2008). The authors proposed the need for this based on the fact that, in dynamic movement, it is an uncommon occurrence for one segment to be in a fixed position for an extended period of time (Chang *et al.*, 2008; Needham *et al.*, 2015). Chang *et al.* (2008) used this technique to quantify segment coordination during straight-line walking; arch kinematics were found to be consistent with extant literature, however it was determined that anti-phase coordination was not exclusively observed, as it had been previously. The presence of forefoot and in-phase inversion, in-phase motions in the sagittal plane, and forefoot adduction was proposed to indicate that previous investigations of rearfoot-forefoot movements were oversimplified (Chang *et al.*, 2008).

The concept of classifying coupling angles was developed further with the aim to establish phase dominance (in-phase or anti-phase), segmental dominance, and additional information on the direction of segmental rotations (Needham *et al*., 2015). A new classification system was determined thus: in-phase with proximal dominancy; in-phase with distal dominancy; anti-phase with proximal dominancy; and anti-phase with distal dominancy (Needham *et al*., 2015). Segmental rotation direction was determined by the position of the coupling angle around the unit circle and the subsequent Cartesian coordinates of the *x* and *y* axes (Needham *et al*., 2015). The authors maintained that the new information gleaned from their modified approach allows opportunities to highlight differences in range of motion at each point in the gait cycle (Needham *et al*., 2015). The approach was used to investigate segmental coordination during the maximal instep kick in football; the aim was to compare their new classification system with that of Chang *et al*. (2008) to examine how the interpretation of movement patterns might be affected (Needham *et al*., 2017). The authors concluded that the more recent classification system, compared with that of Chang *et al*. (2008), provides more information on the interaction between segments. Furthermore, although the focus of this investigation was maximal instep kick, it was suggested that this method could be applied to other movements for an in-depth exploration of segmental coordination patterns (Needham *et al*., 2017).

Evidently, the continual development of this technique denotes that it has advantages in investigating coordination. With the more recent modifications, particularly the use of circular statistics, it is possible to evaluate all cycles of the movement at once. Another aspect that makes vector coding appealing is that there is no need for normalisation, a factor that is often fraught with difficulties or disagreements regarding best practice in other techniques. This also means that the true spatial information in the data is preserved (Hamill *et al*., 2000; Wheat and Glazier, 2006). It can be argued to be a more practical alternative to continuous relative phase, because it deals with movement in terms of joint angles, rather than the potentially more theoretically abstract concept of phase values (Field-Fote and Tepevac, 2002). This may be true in theory; however, the results of vector coding are in fact directions and magnitudes of frame-to-frame vectors rather than actual joint angles which may still be difficult to understand (Wheat and Glazier, 2006). Further, although the additional information provided by Needham *et al*. (2015) may provide additional insight, it also contains aspects that may be conceptually difficult in applied practice.

Further disadvantages to vector coding include that only spatial data are provided, with no quantification of temporal data (Hamill *et al*., 2000; Wheat and Glazier, 2006); this may limit the technique's ability to detect subtle changes in the coordination (Hamill *et al*., 2000). Additionally, it has been suggested that vector coding may be limited when it comes to joints changing direction (Heiderscheit *et al*., 2002). During changes of direction, there will be periods of minimal joint displacement; this will affect the calculation of the coupling angle due to a cluster of data points on the angle-angle plot (Heiderscheit *et al*., 2002; Wheat and Glazier, 2006). Coupling angle sensitivity to small changes in displacement increases with proximity of consecutive data points. Consequently, an incorrect identification of increased variability can occur, which is actually due to a greater proximity of consecutive data points (Heiderscheit *et al*., 2002; Wheat and Glazier, 2006).

2.5.2 Continuous Relative Phase

Continuous relative phase (CRP) as a technique was originally developed to compare the phase space trajectories between two segments or limbs (Lamb and Bartlett, 2017). As such, it demonstrates the relationship at each data point between these segments, throughout a given movement cycle (Wheat and Glazier, 2006). In line with dynamical systems theory, CRP is said to reflect the interaction of different constraints that affect a movement throughout its cycle (Lamb and Bartlett, 2017). Therefore, it is a continuous measure of relative motion, which offers a spatial and temporal evaluation of coordination over the entire movement cycle (Hamill *et al*., 2000).

The CRP parameter is given by subtracting the phase angle of one segment, or oscillator, from that of another, at each data point throughout the sample (Hamill *et al*., 2000; Lamb and Bartlett, 2017; Wheat and Glazier, 2006). The respective phase angles may be calculated either via a phase plot or portrait (a plot of angular displacement against angular velocity, Figure 2.2), or by analytic signals. the majority of studies that have utilised CRP have used the phase-plane portrait but it is also possible to calculate the phase angles with the Hilbert transform (Lamb and Bartlett, 2017).

If using the phase-plane portrait, it is sometimes necessary to first normalise the angular displacement and angular velocity data. If the research question concerns inter-limb coordination, then normalisation may not be necessary, and the plot can simply be centred around the origin (Hamill *et al.*, 2000). However, if the purpose is intra-limb coordination, such as that between two segments or joints of the same limb, it is suggested that normalisation is essential (Hamill *et al.*, 2000). This is to adjust for amplitude differences in range of motion of each segment, and also to centre the phase plot around the origin (Hamill *et al.*, 2000; Wheat and Glazier, 2006). Additionally, the displacement and velocity data then must be interpolated to a fixed number of data points, to enable variability to be calculated (Wheat and Glazier, 2006).

Once these procedures are completed, the normalised displacement and velocity data are used to create the phase-plane portrait. Such a plot, of a variable and its first derivative with respect to time, is considered to accurately reflect the behaviour of a dynamical system (Rosen, 1970, cited in Wheat and Glazier, 2006). The Cartesian coordinates for each point are then converted to polar coordinates, with the phase angle calculated via equation 2.1.

Equation 2.1.

$$\varphi = \tan^{-1}\frac{\omega(t)}{\theta(t)}$$

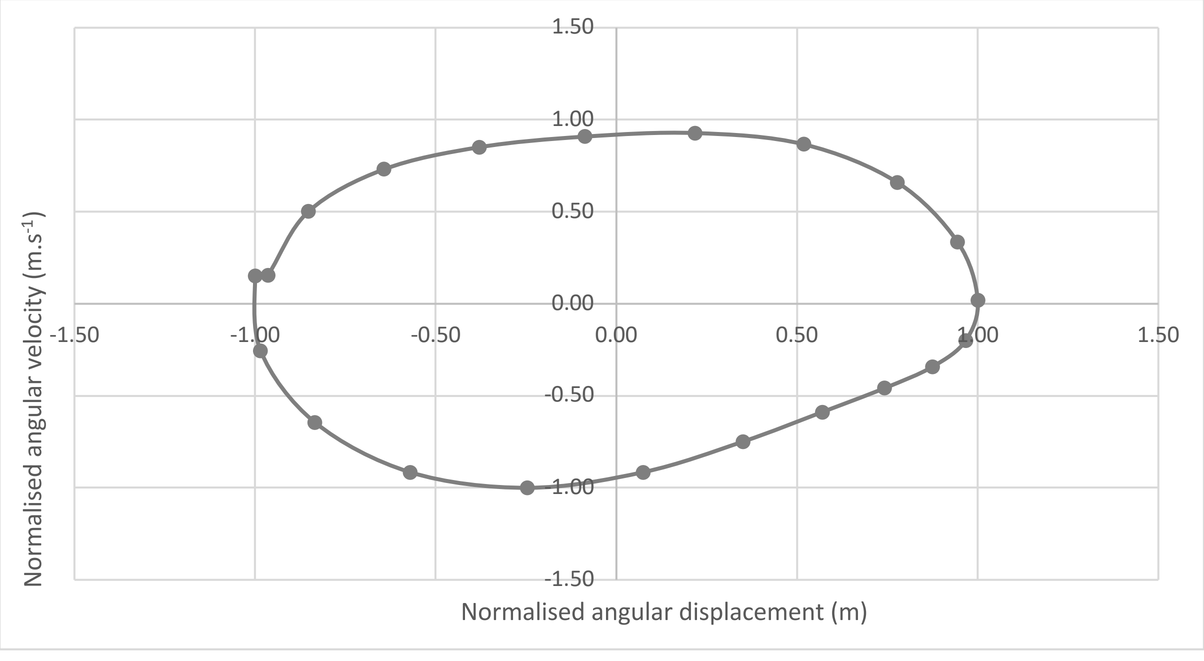


Figure 2.2. Example of a phase-plane portrait. Joint angle data is plotted along the x axis, and angular velocity along the y axis. The phase angle is calculated as the angle between the right horizontal and the line to each data point.

The CRP is then calculated by subtracting one phase angle, representing one joint, from another, representing the other joint.

The outputted phase angle data are within a range of -90 and + 90°. As a result, data must be manipulated to ensure phase angles are calculated within a suitable range (Wheat and Glazier, 2006); what is considered a suitable range differs across the extant literature. Traditionally, 0 to 360° has been used, particularly in the area of motor control, but Hamill *et al*. (2000) stated that as 0° and 360° effectively mean the same thing, this range can cause redundancy in some of the data. The effect on CRP of using different definitions of component phase angles was investigated, and it was concluded that if information about the coordination between segments is required, then 0-360° is required (Wheat *et al*., 2003). This is because information may be masked when using the range of 0-180°, specifically that of anti-phase relationships. It is thought that the 0-180° range was introduced to avoid the discontinuities in phase angles and CRP values that can arise if using the 0-360° range (Wheat and Glazier, 2006). These discontinuities can result in a false sense of high variability if linear statistics are used. However, like vector coding, circular statistics are recommended to analyse CRP, which solves the discontinuity issue. Overall, it is recommended that authors state the definitions they use for phase angle, to enable readers to make an informed interpretation of their data (Wheat *et al*., 2003).

As previously mentioned, it may be necessary to normalise the angle and angular velocity data prior to calculating the phase angles. There are several different methods of doing this, with Hamill *et al*. (2000) stating that normalising to the maximum value of multiple trials will preserve the spatial properties better than if normalising to an individual trial. Issues can arise when normalising each trial to its individual maximum, because it can result in different trials being scaled by different factors; the phase angles will therefore not be affected in a uniform manner (Lamb and Bartlett, 2017). This is suggested not to be a problem if the trials to be evaluated are relatively consistent, yet there appears to be a lack of concrete guidelines determining what level of ‘consistency’ is satisfactory. Hence it is recommended to normalise to the maximum from a group of trials (Hamill *et al*., 2000; Lamb and Bartlett, 2017).

Despite the above recommendation, the presence of outliers in the data can cause distortion if normalising to the maximum of multiple trials (Hamill *et al*., 2000; Lamb and Bartlett, 2017). Any outlier will likely become the reference trial within the normalisation algorithm (Hamill *et al.*, 2000); consequently, a decision must be made as to whether to include or exclude any outliers present. Lamb and Bartlett (2017) recommend centring the phase-planes on zero, and normalise both the angle and angular velocity data to plus or minus one, but acknowledge that there is some disagreement on this. Not normalising the data can affect the variability of the CRP, due to the influence of the proximity of a data point to the origin of the phase plane. The closer two data points, at a fixed distance, are to the origin of a phase-plane, the greater the difference in phase angle observed (Wheat and Glazier, 2006). Consequently, if the data used have small amplitudes, there is potential for erroneously high variability if a normalisation procedure is not undertaken. Fundamentally, the choice of a specific normalisation method should and will depend upon the relevant research question and data to be analysed (Hamill *et al.*, 2000; Wheat and Glazier, 2006).

The advantages of CRP as a technique for quantifying coordination include that it provides temporal, as well as spatial, information, thereby it is more detailed and rigorous in its analysis of behaviour (Hamill *et al.*, 1999). This is a result of including angular velocity data in the calculation of phase angles, which also may make CRP more sensitive to variability in coordination (Wheat *et al.*, 2003). Additionally, coordination and coordination variability can be continuously assessed throughout a whole movement with CRP (Wheat and Glazier, 2006). This enables it to be calculated and compared for different phases throughout a movement cycle. Disadvantages include that CRP ought only to be used if the time histories of the joint motions are sinusoidal (Hamill *et al.*, 2000; Wheat and Glazier, 2006), an assumption which may be violated during some activities. This may sometimes be rectified by centring the phase-plane on the origin, or by using techniques such as Relative Fourier phase.

Additionally, whilst including a higher derivative in the calculation for phase angles has its advantages, it also results in any errors in the data being propagated. Subsequent increased error in the CRP data can be falsely attributed to an increase in variability (Wheat and Glazier, 2006). Continuous relative phase is also limited to the analysis of coordination between no more than two entities (Lamb and Bartlett, 2017); any more than two must be compared in pairs. Further, it has been suggested that the method can be difficult to grasp and relate to conceptually (Mullineaux and Wheat, 2002;

Tepevac and Field-Fote, 2001). It is argued that this could potentially pose issues for practitioners in their interpretation of the relationship between joints and segments (Wheat and Glazier, 2006; Tepevac and Field-Fote, 2001). However, Wheat and Glazier (2006) maintain that this is not so much of a problem if the main aspect of interest is the magnitude of inter- and intra-participant coordination variability.

Research into the coordination of UDK is sparse, particularly using the abovementioned methods. In an attempt to quantify the coordinative patterns within UDK, cross-correlations were calculated to compare movement at the hip, knee, and ankle (Elipot *et al*., 2016). Whilst no significant correlations were found between centre of mass velocity and any of the kinematic variables investigated, significant cross-correlations were found between kinematic variables themselves (Elipot *et al*, 2016). However, it was concluded that cross-correlations may be limited in their capacity to comprehensively explain the complex action of many joints required for UDK (Elipot *et al*., 2016).

The phase relationships of the vertical oscillations of various joints involved in UDK have been compared between skilled and less-skilled swimmers (Connaboy *et al*., 2007). Mean phase angle of the shoulder, hip, knee, and ankle oscillations were calculated via Fourier analysis, in an attempt to establish the presence of propulsive waveforms. The authors maintained that a propulsive waveform could be seen in both groups, yet the skilled swimmers demonstrated a more effective technique due to greater changes in mean phase angle in the distal aspects of the body (Connaboy *et al*., 2007). However, no significant differences in kick frequency or mean phase angle were found between groups, and the remainder of the analysis was qualitative in nature via angle-angle diagrams. The intersegmental coordination of the movement between the trunk and the pelvis during both UDK and butterfly stroke was investigated with CRP (Nikodelis *et al*., 2013). Whilst coordination modes were found to differ between full butterfly stroke and the submerged UDK, no difference was found in the coordination of the pelvis-trunk coupling between prone and supine kick. However, this study only included one female swimmer; therefore, it is difficult to extend results to the wider population. Additionally, no examination of coordination in the lower limbs was conducted, yet it has been established that most of the thrust in UDK is generated by the feet (Sugimoto *et al*., 2008). Consequently, a more thorough quantitative assessment of coordination in elite UDK is warranted.

Conclusion

This chapter aimed to synthesise and review the current body of knowledge regarding determinants of UDK, and identify gaps that may be addressed by future research. It was established that humans are more anatomically constrained than their cetacean counterparts, leading to an asymmetry in the upkick and downkick. Though kick frequency and amplitude are considered to be important in understanding and modifying UDK technique, no consensus was reached on the optimum value for either, nor a definitive relationship established with swimming velocity. It may be that these parameters are specific to the individual, though assessment with an elite cohort may provide further insight. Additionally, a large range of mean swimming velocities in UDK were reported, with no standard definition of this metric in the literature.

The ability to transfer momentum caudally down the chain is considered crucial for UDK performance, by way of a 'body wave' that begins around the trunk or hips and travels towards the feet. No real agreement was established on the significance or ideal range of joint angles or angular velocities to performance. However, ensuring sagittal kick symmetry, and thus two equally propulsive phases, is thought to be important. Propulsion within UDK arises predominantly through the shedding of vortices, with a large vortex observed at the end of the downkick, and the addition of smaller vortices at the end of the upkick for more skilled swimmers. Most of the thrust in UDK is considered to be produced by the feet, and more thrust detected from the downkick than the upkick. It was established that the coordination patterns underpinning UDK are under-researched, and that this area merits further study. Within the limited existing research, skilled swimmers demonstrated more of a 'whip-like' kick movement than unskilled swimmers by way of changes in their mean phase angle along the body. More quantitative analysis of coordinative patterns is required, particularly in an elite cohort.

Though the literature investigating UDK performance is comprehensive, there are areas that remain underexplored. The vast majority of the research has been conducted on prone UDK, with the analysis of supine UDK virtually neglected. Further, the two kicking orientations have rarely been compared, and certainly not with an elite population. Given the underwater phase is no less important in backstroke than freestyle or butterfly, this seems a considerable oversight in the attempt to understand the determinants of UDK performance. Additionally, most studies have been exclusively male or female; those with both sexes tend to pool their data, and do not compare or contrast technique between the two. As such, it is currently unclear if the technique of male and female swimmers differs; if so, it may be that swimmers require different coaching cues based upon what optimises technique for males or females. As stated above, coordination patterns underpinning elite UDK have yet to be adequately quantified, and the difference in coordination between men and women has not been investigated. Finally, little has been completed on the contribution of the upper body, in particular, how the movement of the arms and angular position of the shoulders affects performance.

CHAPTER THREE

GENERAL METHODS

CHAPTER THREE

General Methods

Although further post-processing and resulting analysis differed across Chapters Five, Six, and Seven of this thesis, the same procedures were used to collect data. This section describes those procedures in full, to prevent repetition throughout the thesis. Thereafter, within the aforementioned chapters, readers will be directed to this section for full details of data collection procedures.

3.1 Protocol

All procedures took place in a 50 m heated swimming pool, approximately 2 m in depth, with the moveable boom located in the middle of the pool, resulting in a short-course setup for the duration of the data collection. Participants performed three trials of maximal effort UDK through a calibrated volume while attached to a velocity-meter. Details of the velocity-meter can be found in Chapter Five of this thesis. Their movements were captured by an underwater eight-camera system. All trials commenced from a wall push-off, and concluded with at least one full stroke cycle on the water surface following breakout. One full stroke cycle ensured that the swimmer did not slow down prematurely, thereby affecting the maximal effort of their underwater phase. No instruction was provided to control for depth, so as to obtain an accurate representation of the swimmers' underwater phases as performed in a race situation. Video and velocity-meter data were captured simultaneously.

3.1.1 Three-dimensional video data collection

Participants were prepared for three-dimensional video capture by means of marking up anatomical landmarks. These comprised: distal phalange of the hallux; lateral and medial malleoli; lateral epicondyles of the tibia; right and left greater trochanter; right and left iliac crest; right and left 'upper waist', via the mid-points between the spinous process of T12 and the umbilicus; right and left 'chest', via the mid-points between the spinous process of T7 and the nipples; right and left greater tubercle of the humerus; acromion processes; olecranon processes; styloid processes of each ulna; the most distal point of the 3rd phalange on each hand.

All markers were drawn onto the anatomical landmarks with black permanent marker pen. This was to avoid increasing drag due to skin-mounted 3D markers, the potential altered body mechanics, and to avoid the additional time constraints of reapplying markers that are likely to become detached during a relatively high-velocity push-off from the wall.

Eight standard POI (GigE) cameras (Figure 3.1) (Stemmer Imaging, Mako G223B, Surrey, UK) with full HD resolution (2048-x-1088-px) were submerged 1 m below the surface of the water. Cameras were placed inside protective underwater housings (Figure 3.2) (Autovimation Nautilus IP68) and affixed to weighted tripods (Figure 3.3). Additionally, cameras were connected to two identical desktop computers, each controlling four cameras, via high-speed transfer Ethernet cable. The cameras were placed so as to maximise the field of view of the swimmer, and manually trained and focused on the calibrated volume. A 16 mm lens (Computar M1614MP2) was used, and the aperture was set at f/2.8 to reduce the risk of an overexposed image. The camera settings were adjusted relative to the environment using the capture software (Gecko GigE video recorder v1.9.4, Vision Experts Ltd., Surrey, England).

Figure 3.1. Example of the camera used within the thesis.

Figure 3.2. Example of the underwater housings used within the thesis.

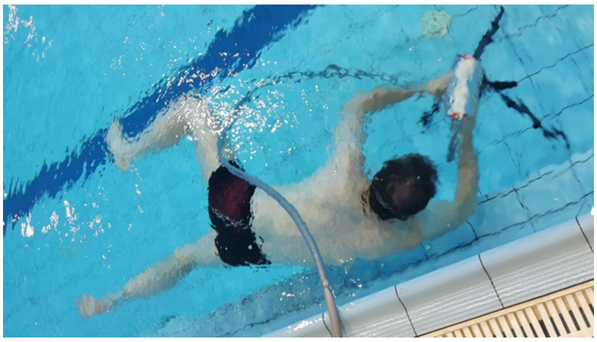


Figure 3.3. Photograph of camera and housing affixed to a weighted tripod.

All footage was captured at 50 Hz direct to the capture PC's hard drives; this rate was considered to be sufficient as it is considerably higher than the Nyquist frequency for swimming, and 25-50 Hz is suggested appropriate for swimming (Payton and Hudson, 2018). The exposure time was set to 1/500 of a second to adequately capture the fastest moving body segments during each trial, typically the extremities (Payton and Hudson, 2018). However, the exposure time was adjusted where necessary between trials, to accommodate the changing natural light levels from the skylights within the ceiling. Upon inspection prior to digitisation, it was confirmed that no blurring was present, indicating the exposure time to be suitable.

3.1.2 Camera calibration

Prior to the main trials, the capture volume was first prepared and calibrated using a custom-built calibration frame measuring 6.15 x 1.50 x 1.20 m. The calibration frame consisted of an arrangement of weighted poles and floats, providing 72 control points of known locations (Figure 3.4).

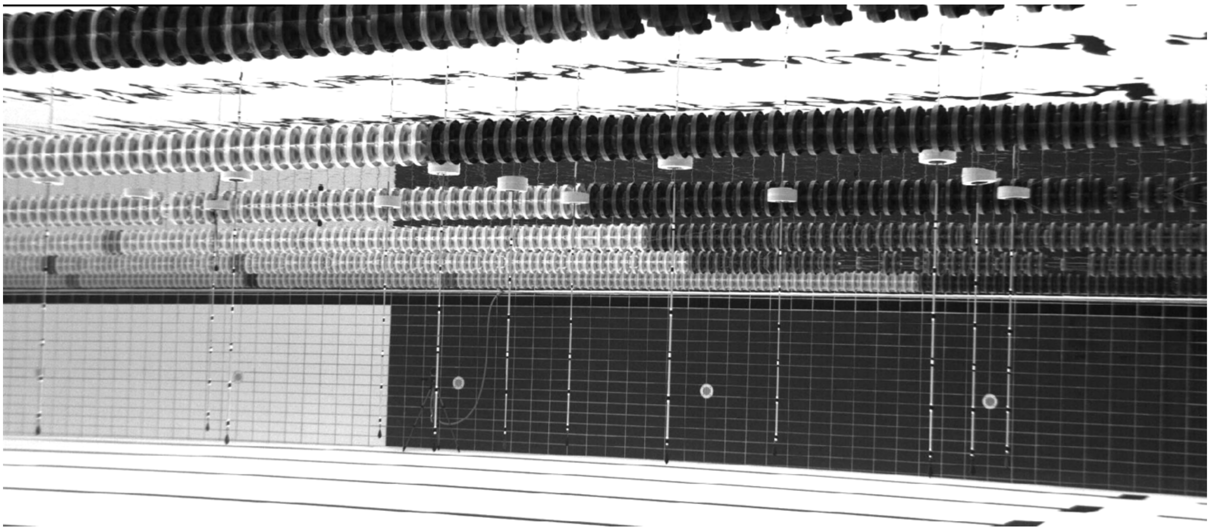


Figure 3.4. Photograph of the calibration frame used for 3D reconstruction in this thesis.

This enabled a right-handed Cartesian coordinate system to be defined (P: xP, yP, zP), in which the *y*-axis constituted the swimming direction, the *z*-axis was directed vertically upwards, and the *x*-axis was in the medio-lateral direction. The frame was assembled and placed within lane 4 of the swimming pool (8.7 m across the pool) and 3.50 m from the end wall, and was secured to the lane rope to maintain its position. As the dimensions of the frame were not sufficient to fill the required volume for this study (and the field width of the cameras was ~7 m) two calibrations were completed as follows:

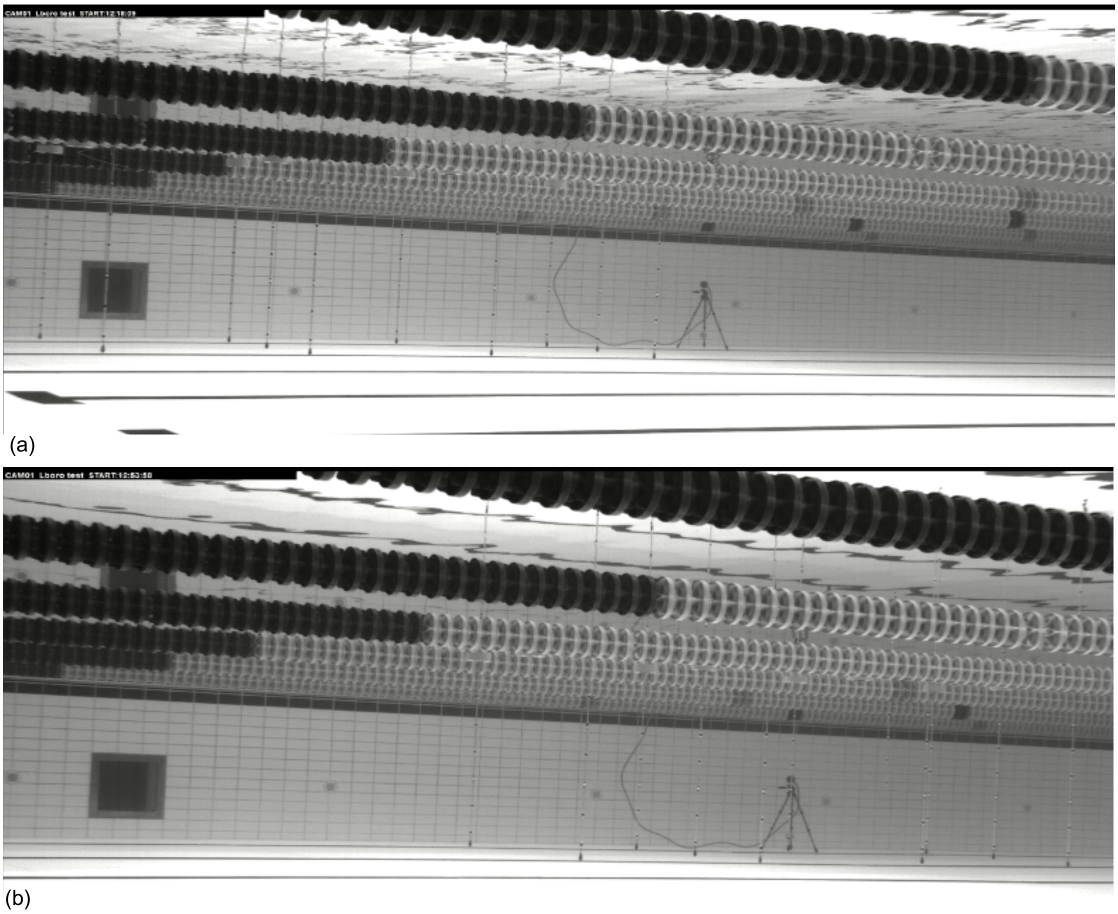
Calibration 1

The calibration frame was positioned 2.65 m from the end wall. A laser measure was used to record the frame's location (± 1 mm) from the side and end of the pool. All measurements were repeated three times. The frame was recorded in this location from the first set of four cameras – this was designated Calibration 1 (Figure 3.5[a]).

Calibration 2

The calibration frame was then translated 3.50 m in the swimming direction (y-axis) to extend the calibration volume. Laser measurements were used to ensure that the frame's position along the x-axis remained unchanged. The frame was then recorded again from the second set of four cameras – this was designated Calibration 2 (Figure 3.5[b]).

Following data collection, the control points of the calibration frame were digitised using the commercial software SIMI Motion 3D (SIMI Reality Motion Systems GmBH, version 9.2, Germany) to provide a set of two-dimensional coordinates for each control point. These sets of coordinates were then used to generate the 11 direct linear transform (DLT) coefficients required to obtain 3D coordinates for each of the markers on the participants. A reconstruction error check was performed, to determine if the 3D reconstruction errors were within acceptable limits (Payton and Hudson, 2017). Mean root mean squared error (RMSE) values for Calibration 1 were 3.2 mm, 3.4 mm, and 3.7 mm for the x, y, and z coordinates respectively. Mean RMSE values for Calibration 2 were 2.4 mm, 2.1 mm, and 2.2 mm for the x, y, and z coordinates respectively. All values were lower than those reported by Sanders *et al*. (2006), of 3.9 mm, 3.8 mm, and 4.8 mm for the x, y, and z coordinates respectively, for a frame measuring 1.5 m x 1.5 m x 1.0 m and a calibrated volume of 6.75 m^3. As the RMSE



(a)

(b)

Figure 3.5: (a) the calibration frame in the initial position; (b) the calibration frame following translation along the y-axis.

values in this thesis were lower for a calibrated volume of 11.07 m^3, the camera calibration error was considered acceptable.

3.2. Data processing and analysis.

Where possible within the experimental trials, automatic digitisation was performed for all eight camera views within SIMI Motion 3D software. Automatic tracking was predominantly possible for the more proximal markers, e.g., hip. All other markers were manually digitised from entry into the calibrated volume to breakout. For freestyle and backstroke, breakout was defined as the instant the arm breaks the surface of the water to begin stroking; for butterfly, breakout was defined as the instant the head breaks the surface of the water.

Following complete digitisation of all markers, the raw data were filtered with a quintic spline, with an error variance of 0.0001. Subsequently, reconstruction based upon 3D-DLT was again performed to obtain 3D coordinates of the body landmarks, and a 14-segment centre of mass model was defined (Dempster, 1955). A study comparing three different COM models and their effect on estimation of swimming velocity found that interpretation of velocity was unaffected by the choice of model (van der Westhuizen, 2021). Though Dempster was not assessed in this study, De Leva's model was included. Consequently, for the purposes of this thesis, an analysis was undertaken to compare COM velocity calculated from Dempster and De Leva models; no deviation was found between the two, thus Dempster was considered sufficient.

In order to assess intra-rater reliability, repeat digitisations were completed of a randomly selected trial, and RMSE (Challis, 2017) was used to estimate the precision of the digitisation of the 17 markers used to create the centre of mass model. All RMSE values were below 1 mm, with the exception of the left toe in all three directions (3.17 mm, 1.59 mm, and 1.58 mm in the x, y, and z directions respectively) and the right toe in the x and y directions (2.15 mm and 1.13 mm respectively).

Specific processing, analysis, and statistical analysis are detailed in each individual chapter as required, as well as participant information. Additionally, whilst some participant characteristics were recorded, anthropometric measures were not collected from every participant. The collection of anthropometric variables was neglected in earlier studies, and due to athletes retiring or moving to other programmes, it was not possible to collect them retrospectively. Consequently, an analysis of such variables could not be completed.

CHAPTER FOUR

An Assessment of Great Britain's Start and Turn Performance

CHAPTER FOUR

An Assessment of Great Britain’s Start and Turn Performance

4.1 Introduction

The practice of race analysis at swimming competitions involves the collection of video footage and the subsequent analysis, thereby providing evaluative and tactical information to the coach and athletes. As such, race analysis, and the resulting data, has become an integral aspect of swimming competitions (Cossor and Mason, 2001). Within a sport whose competitions can take place over the course of two weeks, analysis can provide context and a breakdown of the race, which is often useful between heats and finals, and planning for events later in the competition. Analysis can also provide information to athletes and coaches about their own and competitors’ performances. Further, it allows for longer-term technical and tactical planning and periodisation; with a large enough database, it is possible to detect patterns and trends, and make more accurate predictions. However, it is important to remember that for this information to transfer into such advantages, it must be effectively communicated to coaches and athletes. If not, it is highly unlikely that the coaches will be engaged, and therefore much less likely to use the information to help inform training programmes and skill acquisition (Arellano, 2004).

Analysis at major swimming competitions has taken place for decades, often forming the basis for a variety of scientific investigations (Kennedy *et al*., 1990; Arellano *et al*., 1994; Cossor and Mason, 2001; Chatard *et al*., 2001; Hellard et al., 2008; Veiga *et al*., 2016). From the 1988 Seoul Olympics, the heats of all of the 100 m events were analysed, comprising results from 221 male and 176 female swimmers (Kennedy *et al*., 1990). Stroke length was found to be negatively correlated to final time for most events, with the authors suggesting it is the dominant component of swimming speed (Kennedy *et al*, 1990). Additionally, an inverse relationship was established between stroke length and stroke rate, with faster swimmers using longer stroke lengths (Arellano *et al*., 1994). Contrastingly, Chatard *et al*. (2001) found the opposite, as the medalists in their study used shorter stroke lengths and higher stroke rates than the rest of the finalists in all four laps. However, Arellano *et al*. (1994) included 335 swimmers in their cohort, across the 50 m, 100 m, and 200 m freestyle events, whereas Chatard *et al*. (2001) analysed only women’s 200 backstroke for 16 athletes.

The interaction between stroke rate and stroke length is often dependent upon a swimmer's anthropometrics (Morais *et al*., 2012; Barbosa *et al*., 2014; Figueiredo *et al*., 2016); thus, participant characteristics may have contributed to differing results. Further, the finding that medalists used shorter stroke lengths over the 200 m race is surprising given that, in longer races, stroke rate tends to decrease in favour of a larger stroke length (Craig *et al*., 1985). Of note, however, is that Kennedy et al. (1990) and Arellano et al. (1994) did not include a measure of instantaneous stroke rate over the entire race, but instead calculated rate over four or five stroke cycles, to provide an average measure. This was most likely due to the limitations of technology at the time and is often an acceptable method of estimation within a training session, yet may have some bearing on the results, particularly when conclusions are then drawn on the impact of stroke rate. Nevertheless, Hellard *et al*. (2008) also found that Olympic swimmers exhibited higher stroke rates in backstroke than National swimmers, and that stroke length and stroke rate differed between strokes. Olympic swimmers have also demonstrated less stroke rate variability in backstroke and freestyle than National swimmers (Hellard *et al*., 2008). Further, in 200 m butterfly, freestyle, and backstroke, stroke rate variability decreased during the second lap for all swimmers (Hellard et al., 2008).

The importance of starts and turns to race performance was recognised by Arellano *et al*. (1994), asserting that the various aspects of the race, including starting, turning, and finishing times, evidently affect the outcome of any race (Arellano *et al*., 1994). A strong inverse relationship was found between stroke length and stroke rate, and start and turn times correlated with race time over every race distance (Arellano *et al*., 1994). This was a useful preliminary investigation into the relative significance of start, turn, and finishing metrics on final race time. However, turn-in and turn-out times were measured as 7.5 m in and 7.5 m out respectively, whereas the most recent standardised distances are 5 m in and either 10 m or 15 m out. Additionally, the authors used the 10 m mark to determine start time, and finish time was calculated as the time taken to swim the final 10 m; these metrics are usually calculated using the first 15 m and the final 5 m respectively. The distance of 7.5 m to denote the turn was also used in a study that aimed to determine if medallists at the Olympics employed a specific race strategy compared with finalists and semi-finalists of the 200 backstroke (Chatard *et al*., 2001). Turn velocity for all three turns was not significant between groups, however the overall 200 m velocity was related to the third turn velocity for the whole sample ($r = 0.60$, $p < 0.01$) (Chatard *et al*., 2001). These findings are interesting, yet it is difficult to relate them to more recent research and performances due to inconsistencies in distance definitions.

The interaction between the underwater elements of a swimming race and overall race performance was studied by Veiga *et al*. (2016). Specifically, the relationship between distance travelled underwater during the start and turns with race performance was examined. Eight cameras positioned above the water recorded the 100 and 200 m events during the FINA 2013 World Championships, with 256 performances included in analysis. Start and turn distances and average velocities were calculated, from the starting or turning wall to head emersion (Veiga *et al*., 2016). Contrary to their hypothesis, it was found that faster swimmers did not categorically spend longer underwater than did slower swimmers (Veiga *et al*., 2016), particularly within the 100 m events. More of a pattern emerged for the 200 m swimmers than the 100 m swimmers to spend longer underwater, predominantly observed in butterfly and backstroke. This may be due to a racing strategy, in which these athletes maximise their time swimming underwater to save energy due to the reduction in drag under the surface (Lyttle *et al*., 2000; Veiga and Roig, 2016). The authors maintained that freestyle swimmers should maximise their velocity during the turns, rather than their time underwater, yet swimmers in other events should increase or maintain their underwater distance; this was particularly evident for the last turn with 200 m events (Veiga *et al*., 2016).

Race analysis research has demonstrated that starts and turns account for a considerable proportion of final race time. Specifically, it has been postulated that start time, finishing time, and turn times (where applicable) have a significant role in 50 m, 100 m, and 200 m freestyle events (Arellano *et al*., 1994). The underwater phase of the start has been found to significantly negatively correlate with men's 100 m events in all strokes, and with women's 200 m butterfly, breaststroke, and freestyle, and 100 m backstroke (Cossor and Mason, 2001). Furthermore, the time from wall contact to travel a fixed distance from the wall was found to significantly correlate with total turn time in most of the men's and women's events (Cossor, 2014). The importance to final race time of executing a good start naturally increases as race distance decreases, due to the concurrent reduction in time spent swimming at the surface where there is an increase in drag. As an example, the start time represented 26% of total race time for sprint events at two separate Olympic Games (Cossor and Mason, 2001). Additionally, start time to 15 m has been found to differentiate between skill level of two groups of swimmers, with skilled swimmers reaching 15 m significantly faster than less skilled swimmers (Marinho *et al*., 2021). As such, it is expected that start times will correlate highly to final race time in shorter events.

The swimming start can be divided into three sub-phases: the block phase, flight phase, and underwater phase. The time contribution of the underwater phase to the overall start time, and consequently the final race time, is the largest of the three sub-phases, and has been approximated at 84% (Slawson *et al*., 2013). This sub-phase consists of a glide phase as well as a kicking phase; the glide is likely the fastest that the athlete will travel once they are in the water, providing they capitalise on the momentum from the block and flight phases and not commence kicking too early (Elipot *et al*., 2010; Lyttle *et al*., 2000; Tor, 2015). This is also applicable to turns, as it is important tactically to use the momentum gained from pushing off the wall and optimally time the beginning of the kicking phase. In contrast to starts, the significance of executing a good turn becomes more evident as race distance increases. Whilst it is important to turn well during any race, the number of turns within a race clearly increases with longer races. As such, even small improvements per turn can amount to a large overall improvement in total turn time, and thus final race time (Morais *et al*., 2019), indicating the important relationship between turn time and final race time.

In-depth analysis of races within British Swimming is currently undertaken with the use of Nemo Race Analysis System, a bespoke software package developed by Sheffield Hallam University. Nemo enables race footage to be loaded, explored, and tagged, thereby generating a variety of relevant metrics required to quantify performance. These metrics include: split times; times to pre-determined distances (e.g., 5 m, 15 m, 25 m); stroke counts and rates; rotation times, and so on. A selection of the metrics calculated via Nemo offer the potential to explore starts and turn performance. For example, the time it takes for an athlete to reach 15 m is commonly used as a measure of start performance (Cossor and Mason, 2001; Tor *et al*., 2015). A thorough exploration of GB swimmers' times to 15 m, compared with medallists from other nations, will quantify the current effectiveness of Great Britain's (GB) swimmers' starts and turns. As the present thesis concerns UDK, an assessment of these times in backstroke, butterfly, and freestyle is warranted. Subsequently, it may be established whether this is a worthwhile area to prioritise for performance improvement, thereby informing coaching and sports science support for present and upcoming athletes.

4.1.1 Aims

The aims of this study were to:

- establish whether start and turn times are associated with final race time for backstroke, butterfly, and freestyle races over distances from 50 m to 200 m
- determine how the start and turns times, alongside clean swim speeds, differ between top-performing GB athletes and medallists from the rest of the world.

4.1.2 Hypotheses

It was hypothesised that:

1. start times would correlate more highly with final race time within shorter events (i.e., 50 m)
2. turn times would correlate more highly with final race time in longer events (i.e., 200 m)
3. GB athletes would have slower start and turn times, with reference to their clean swim speeds, compared with other nations.

4.2 Methods

4.2.1 Procedures

Existing retrospective data within the British Swimming race analysis system were used for this study. The Nemo database comprises analysis at all major competitions from 2010 to present day. This database was systematically searched for relevant competitions and events, and appropriate metrics were extracted. Inclusion criteria for races were long-course competitions, freestyle, backstroke, and butterfly finals of distance up to 200 m (i.e., 50 m, 100 m, and 200 m races) between 2014 and 2018 and of a ‘world-class’ standard. Within these criteria, the competitions that were included were two Commonwealth Games (2014 and 2018), three European Championships (2014, 2016, and 2018), two World Championships (2015 and 2017), and one Olympic Games (2016). As a result, 131 participants were included in the analysis: 43 GB athletes, and 88 non-GB athletes.

A standard procedure for race analysis took place at each competition. Analysts for British Swimming were situated within the highest level of spectator seating, each with an HD camera positioned approximately perpendicularly to the 25 m mark (i.e., the middle) of the pool. A standard calibration procedure is carried out at each competition. First, the length of the pool is measured and markers are affixed to the poolside at regular intervals, namely 5 m, 15 m, 25 m, 35 m, and 45 m. This is completed on both sides of the pool. Following this, photographs are taken of the pool from an aerial position so that the markers may be seen on both sides of the pool. Lines are then drawn over the photographs between each set of markers, resulting in lines at each interval corresponding to each distance position. Cameras each sampled at 50 Hz and were attached to a tripod affixed to the ground, ensuring reliable and repeatable camera positioning for all races. Cameras panned the length of each race, tracking relevant swimmers, and videos were imported into the Nemo race analysis system. Subsequent analysis consisted of manual entry of split times (i.e., the time taken for each lap of the pool), tagging of strokes, and the time taken for the swimmer's head to reach the predetermined distances. A previous study demonstrated that the error between times measured with Nemo and a gold standard ranged between 0.006 ± 0.05 s (at the 25 m mark) and -0.133 ± 0.14 s (at the 45 m mark) (Kelley, 2014).

4.2.2 Variables

Race variables from the top three performers, for both males and females, for Great Britain and those of the medallists were extracted for each event. These were:

- **Race time** – the official time taken to complete the race.
- **Clean swim speed** – the speed during free swimming elements of the race, that is, those aspects of the race not including starts and turns. This includes the sections of the race between 15 m and 45 m of each lap.
- **Start time** – time between the start signal and the athlete's head reaching the 15 m mark.

- **Turn out time** – time between wall contact and the athlete’s head reaching the 15 m mark. This metric was used because, of the metrics available from the Nemo database, it most closely reflects UDK performance.
- **Turn 1, 2, and 3 out** – within 200 m races, the time that athlete’s head passed the 15 m mark on turn 1, 2, and 3 respectively.

The above variables were extracted from each race’s analysis and placed within a database in Microsoft Excel. Within 200 m events, where there are three turns per race, a mean of the three turns was also calculated for each race within the database, resulting in a single time to 15 m. Additionally, a mean each of Turn 1, 2, and 3 15 m out times per athlete for each event was calculated. For example, if an athlete had more than one 200 m butterfly race within the database, a mean of their Turn 1 time was calculated, followed by a mean of their Turn 2 time, and finally a mean of their Turn 3. In some events, there were multiple entries for certain athletes (e.g., that athlete competed in 200 m freestyle at several competitions within the analysis), whereas other athletes had only one entry within the database. To mitigate this discrepancy and to enable comparison across events, means for each variable were calculated for each athlete within the database, resulting in one value per metric for each athlete within each event.

4.2.3 Statistical analysis

Data were analysed with IBM SPSS Statistics for Windows (Version 27.0, Armonk, NY: IBM Corp.). Data were assessed for normality and homogeneity of variance and were found to be non-normal. As such Spearman’s Rho correlations were performed on the pooled nation data to assess the presence and strength of an association between race time and key race metrics. Correlations were performed between race time and average start time, and race time and average turn out time for each event. The strength of correlation coefficients was defined as follows: 0 -.19 = very weak, .20 - .39 = weak, .40 - .59 = moderate, .60 - .79 = strong. .80 - 1.00 = very strong (Matsuda *et al.*, 2021).

Due to non-uniformity in variance and a few groups within the analysis comprising small sample sizes (e.g., n = 2), inferential statistics were considered inappropriate. Thus, the remainder of the analysis is descriptive. In order to compare times to 15 m and clean swim speeds, an average start time, turn out time, and clean swim speed was calculated for each event and gender, for both GB athletes and non-GB athletes. To look more deeply at trends within turn times, the turn out times for turns 1, 2, and 3 were compared to determine if athletes' turn times got slower throughout the race.

4.3 Results

4.3.1 Correlations

There were strong significant, positive correlations between race time and start time for men's: 50 m freestyle (r_s = .66, p = .03); 100 m backstroke (r_s = .65, p = .02); and 200 m backstroke (r_s = .78, p = .01). No strong correlations between race time and start time were found for any women's events, however moderate significant positive correlations were found for 100 freestyle (r_s = .58, p = .04) and 200 freestyle (r_s = .58, p = .04). Between race time and turn out time there was a very strong significant, positive correlation for women's 200 m freestyle (r_s = .80, p = .001). There were also strong significant, positive correlations for women's 100 m backstroke (r_s = .74, p = .01), women's 100 m freestyle (r_s = .70, p = .01), women's 200 m butterfly (r_s = .78, p = .001), and men's 200 m freestyle (r_s = .64, p = .03). There was also a strong positive correlation between race time and start time for men's 50 m backstroke that was non-significant (r_s = .69, p = .06).

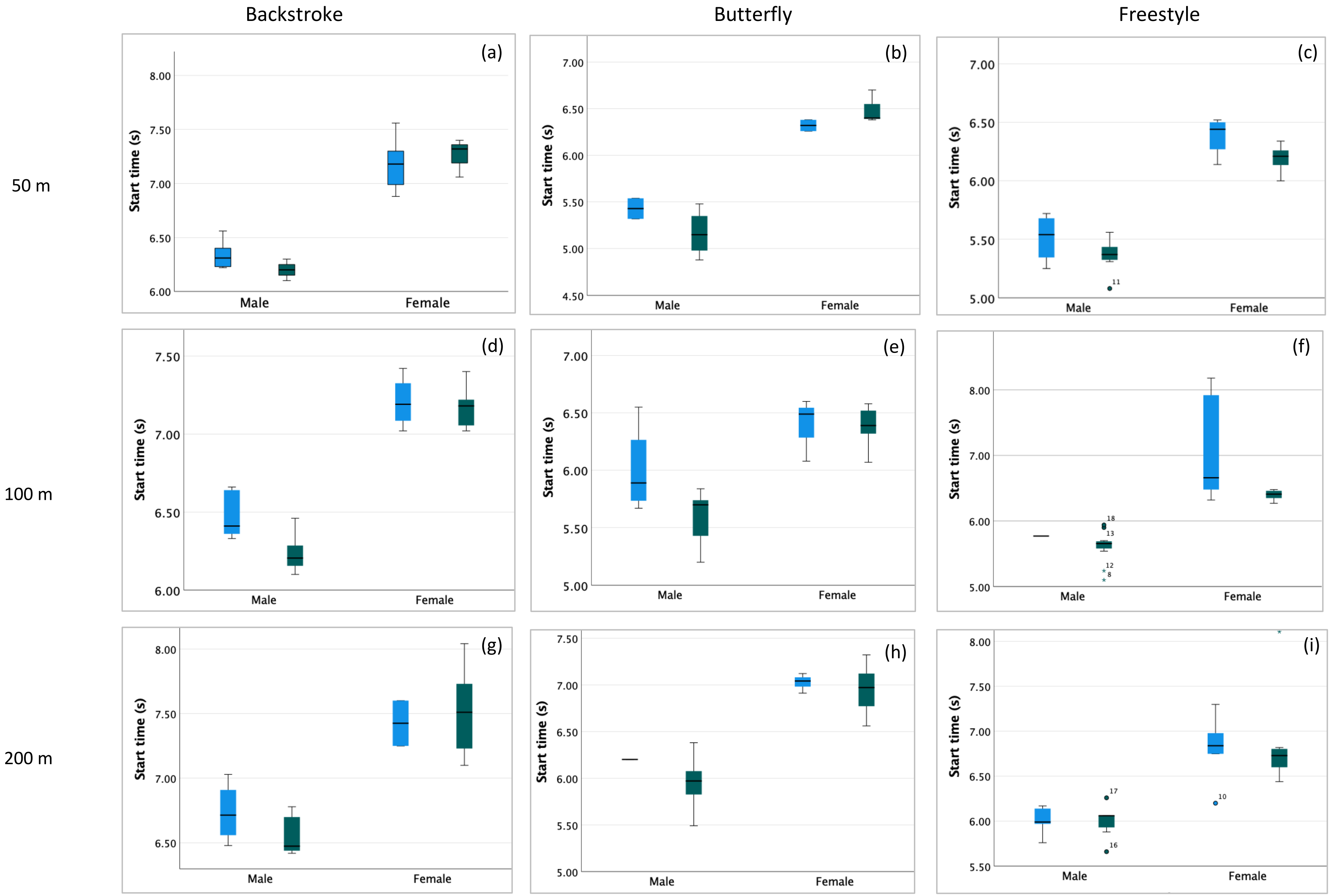


Figure 4.1. Box plots showing start times of GB and non-GB athletes for (a) 50 m backstroke, (b) 50 m butterfly, (c) 50 m freestyle, (d) 100 m backstroke, (e) 100 m butterfly, (f) 100 m freestyle, (g) 200 m backstroke, (h) 200 m butterfly, (i) 200 m freestyle. Blue bars represent GB, green bars represent non-GB.

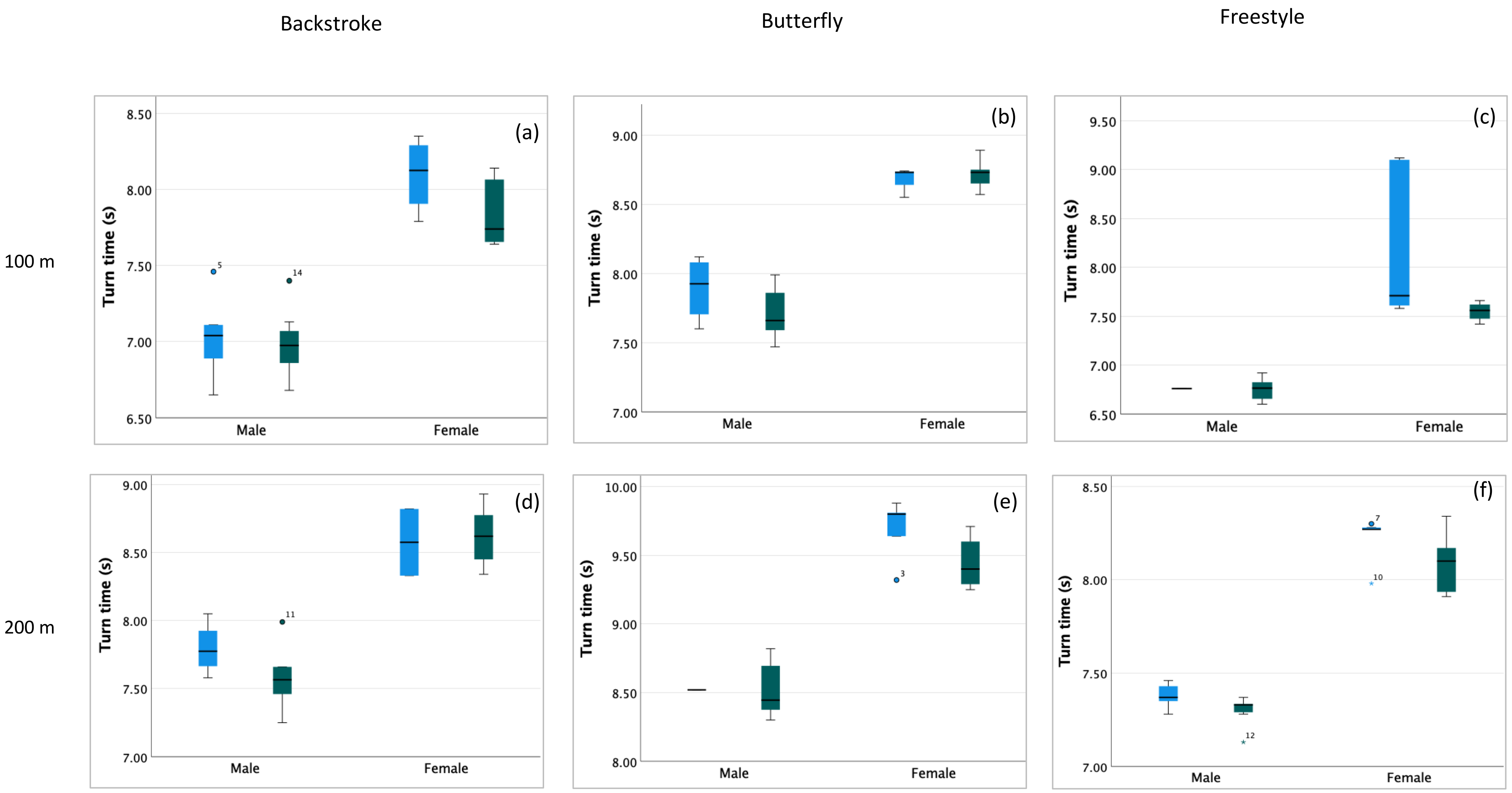


Figure 4.2. Box plots showing turn out times of GB and non-GB athletes for (a) 100 m backstroke, (b) 100 m butterfly, (c) 100 m freestyle, (d) 200 m backstroke, (e) 200 m butterfly, (f) 200 m freestyle. Blue bars represent GB, green bars represent non-GB.

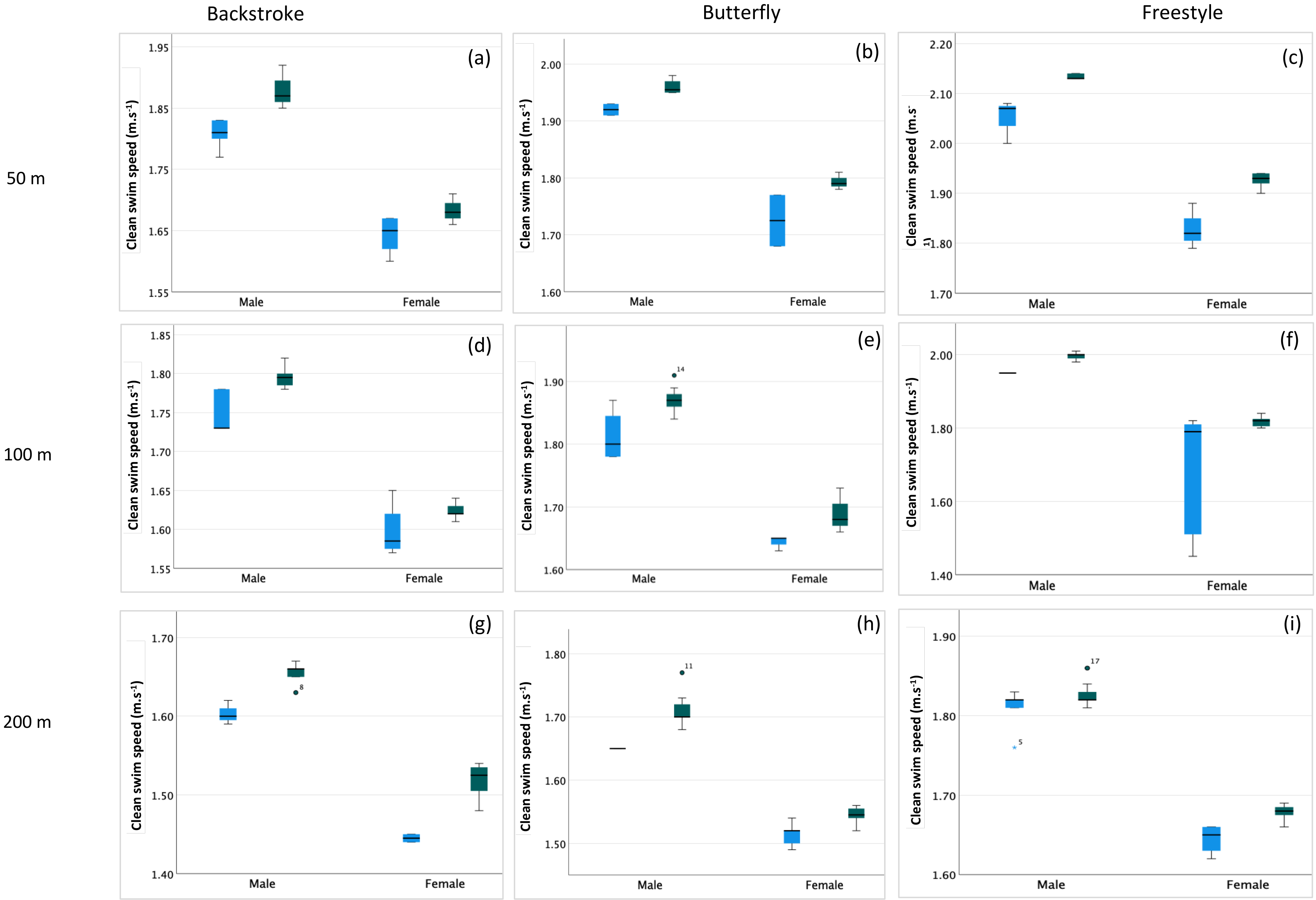


Figure 4.3. Box plots showing clean swim speeds for GB and non-GB athletes for (a) 50 m backstroke, (b) 50 m butterfly, (c) 50 m freestyle, (d) 100 m backstroke, (e) 100 m butterfly, (f) 100 m freestyle, (g) 200 m backstroke, (h) 200 m butterfly, (i) 200 m freestyle. Blue bars represent GB, green bars represent non-GB.

Table 4.1. Mean ± standard deviations of start times, turn out times, and clean swim speeds for male GB and non-GB athletes. * indicates a significant correlation with race time.

	Start time (s)		**Turn out time (s)**		**Clean swim speed ($m.s^{-1}$)**	
	GB	**Non-GB**	**GB**	**Non-GB**	**GB**	**Non-GB**
50 m Backstroke	6.34 ± 0.14	6.20 ± 0.10	—	—	1.81 ± 0.02	1.88 ± 0.04
50 m Butterfly	5.43 ± 0.16	5.17 ± 0.25	—	—	1.92 ± 0.01	1.96 ± 0.01
50 m Freestyle	5.51 ± 0.21*	5.36 ± 0.15*	—	—	2.06 ± 0.04	2.13 ± 0.01
100 m Backstroke	6.48 ± 0.16*	6.23 ± 0.11*	7.03 ± 0.30	6.98 ± 0.22	1.75 ± 0.03	1.79 ± 0.01
100 m Butterfly	6.00 ± 0.38	5.59 ± 0.22	7.89 ± 0.23	7.71 ± 0.18	1.81 ± 0.04	1.87 ± 0.02
100 m Freestyle	5.77 ± 0.00	5.61 ± 0.24	6.76 ± 0.00	6.75 ± 0.11	1.95 ± 0.00	2.00 ± 0.01
200 m Backstroke	6.74 ± 0.23*	6.55 ± 0.15*	7.79 ± 0.19	7.58 ± 0.25	1.60 ± 0.01	1.65 ± 0.01
200 m Butterfly	6.10 ± 0.14	5.95 ± 0.26	8.54 ± 0.04	8.52 ± 0.19	1.64 ± 0.01	1.71 ± 0.03
200 m Freestyle	6.01 ± 0.16	5.99 ± 0.19	7.38 ± 0.07*	7.30 ± 0.08*	1.81 ± 0.03	1.83 ± 0.02

Table 4.2. Mean ± standard deviations of start times, turn out times, and clean swim speeds for female GB and non-GB athletes. * indicates a significant correlation with race time.

	Start time (s)		**Turn out time (s)**		**Clean swim speed ($m.s^{-1}$)**	
	GB	**Non-GB**	**GB**	**Non-GB**	**GB**	**Non-GB**
50 m Backstroke	7.18 ± 0.27	7.26 ± 0.18	—	—	1.64 ± 0.03	1.68 ± 0.03
50 m Butterfly	6.32 ± 0.08	6.49 ± 0.18	—	—	1.73 ± 0.06	1.79 ± 0.02
50 m Freestyle	6.39 ± 0.17	6.19 ± 0.12	—	—	1.83 ± 0.04	1.93 ± 0.02
100 m Backstroke	7.20 ± 0.17	7.16 ± 0.13	8.10 ± 0.25*	7.85 ± 0.23*	1.60 ± 0.03	1.62 ± 0.01
100 m Butterfly	6.39 ± 0.27	6.39 ± 0.18	8.67 ± 0.11	8.71 ± 0.10	1.64 ± 0.01	1.69 ± 0.03
100 m Freestyle	7.11 ± 0.87*	6.40 ± 0.07*	8.22 ± 0.81*	7.55 ± 0.09*	1.68 ± 0.18	1.82 ± 0.01
200 m Backstroke	7.43 ± 0.25	7.51 ± 0.32	8.57 ± 0.35	8.62 ± 0.21	1.45 ± 0.01	1.52 ± 0.02
200 m Butterfly	7.03 ± 0.08	6.95 ± 0.25	9.69 ± 0.22*	9.44 ± 0.18*	1.51 ± 0.02	1.54 ± 0.01
200 m Freestyle	6.81 ± 0.40*	6.85 ± 0.52*	8.22 ± 0.14*	8.08 ± 0.15*	1.64 ± 0.02	1.71 ± 0.08

Table 4.3. Mean ± standard deviations of turn 1, 2, and 3 out times for male GB and non-GB athletes.

	Turn 1 out (s)		Turn 2 out (s)		Turn 3 out (s)	
	GB	**Non-GB**	**GB**	**Non-GB**	**GB**	**Non-GB**
200 m Backstroke	7.80 ± 0.17	7.53 ± 0.23	7.80 ± 0.13	7.61 ± 0.31	7.78 ± 0.30	7.68 ± 0.30
200 m Butterfly	8.40 ± 0.01	8.39 ± 0.12	8.57 ± 0.03	8.57 ± 0.20	8.66 ± 0.08	8.67 ± 0.35
200 m Freestyle	7.31 ± 0.08	7.19 ± 0.10	7.39 ± 0.08	7.25 ± 0.05	7.43 ± 0.10	7.45 ± 0.15

Table 4.4. Mean ± standard deviations of turn 1, 2, and 3 out times for female GB and non-GB athletes.

	Turn 1 out (s)		Turn 2 out (s)		Turn 3 out (s)	
	GB	**Non-GB**	**GB**	**Non-GB**	**GB**	**Non-GB**
200 m Backstroke	8.49 ± 0.15	8.50 ± 0.27	8.66 ± 0.30	8.64 ± 0.21	8.57 ± 0.59	8.75 ± 0.21
200 m Butterfly	9.53 ± 0.27	9.36 ± 0.23	9.65 ± 0.16	9.49 ± 0.09	9.89 ± 0.30	9.48 ± 0.27
200 m Freestyle	8.10 ± 0.21	8.00 ± 0.26	8.20 ± 0.16	8.04 ± 0.14	8.36 ± 0.14	8.21 ± 0.17

Table 4.5. Correlation values for start and turn out times for all events analysed. * indicates a significant correlation with race time at the p < 0.05 level; ** indicates a significant correlation with race time at the p < 0.01 level.

Event	Sex	Start time	Turn out time
50 m Backstroke	Male	.69	-
	Female	.24	-
50 m Butterfly	Male	-.09	-
	Female	.41	-
50 m Freestyle	Male	.66*	-
	Female	.60	-
100 m Backstroke	Male	.65*	.34
	Female	.05	.74**
100 m Butterfly	Male	.44	.43
	Female	.27	.15
100 m Freestyle	Male	.10	.29
	Female	.58*	.72**
200 m Backstroke	Male	.78**	.52
	Female	.06	.07
200 m Butterfly	Male	.52	.32
	Female	.50	.79**
200 m Freestyle	Male	-.28	.63*
	Female	.58*	.80**

4.3.2 Clean swim speeds

Tables 4.1 and 4.2 show that mean clean swim speeds were higher for non-GB athletes than for GB athletes in all events, for both genders. The highest clean swim speeds were observed in the 50 m freestyle, and the lowest in 200 m backstroke. Male swimmers were consistently faster than female swimmers in all events. For each distance (50 m, 100 m, and 200 m), freestyle events had the highest clean swim speeds, followed by butterfly, and then backstroke.

4.3.3 Starts

Male swimmers' start times were faster than those for female swimmers for all events and across all nations (Table 4.1). However, male swimmers from Great Britain were, on average, slower to 15 m than were male non-GB swimmers in all events; this was most pronounced in 100 m butterfly, with a 0.41 s difference. Further, butterfly demonstrated the largest discrepancy between GB and non-GB athletes for 50 m (0.26 s) and 100 m events (0.41 s); for 200 m events, backstroke had the largest difference (0.19 s). The smallest difference was found in 200 m freestyle (0.01 s). In contrast, GB female swimmers were faster to 15 m than female non-GB swimmers in 50 m backstroke, 50 m butterfly, 200 m backstroke, and 200 m freestyle (Table 4.2). This discrepancy was most pronounced in 50 m butterfly in which GB female swimmers' starts were 0.17 s faster than those of the non-GB swimmers. However, they had, on average, 0.71 s slower starts in 100 m freestyle than the non-GB swimmers and had the same average start time in 100 m butterfly (6.39 s). Whilst GB female athletes were faster than their non-GB counterparts in some events, a systematic pattern in which GB female athletes are better at a particular distance or stroke was not observed.

4.3.4 Turns

With regards to turn-out times male swimmers were again faster than female swimmers for all events and across all nations. For 100 m events, in which there is only one turn, GB male swimmers' turn-out times were longer than those of the non-GB swimmers across all three strokes. However, this was only by 0.01 seconds in 100 m freestyle. The biggest discrepancy was found in 100 m butterfly (0.18 s slower), followed by 100 m backstroke (0.05 s slower), and then 100 m freestyle (0.01 s slower). Further, GB female swimmers were faster to 15 m than were non-GB swimmers for 100 m butterfly (0.04 s), but slower for the other two strokes (0.25 s slower for backstroke; 0.67 s slower for freestyle).

In the 200 m events for all three strokes, GB males had slower turn-out times than non-GB swimmers (difference of 0.21 s for backstroke, 0.02 s for butterfly, 0.08 s for freestyle) (Table 4.1). In contrast, GB female swimmers had 0.05 s faster turn-out times than non-GB swimmers for 200 m backstroke, yet 0.25 s and 0.14 s slower for 200 m butterfly and 200 m freestyle respectively (Table 4.2). When assessing the three turn times individually, for 200 m backstroke 30% of all swimmers had the shortest time on their last turn compared with the preceding two (Table 4.3). Assessing GB and non-GB groups individually, 50% of the GB swimmers and 21% of non-GB swimmers had the third turn as their fastest. For 200 m butterfly, 13% of all swimmers were fastest on their last turn; none of these were GB swimmers, indeed all GB swimmers' third turns were their slowest. Finally, for 200 m freestyle, only one swimmer out of the cohort had the shortest time on their third turn; this was a GB swimmer.

4.4 Discussion

The aims of this study were to establish whether start and turn times are associated with final race time for backstroke, butterfly, and freestyle races over distances from 50 m to 200 m, and to determine how the start and turns times, alongside clean swim speeds, differ between top-performing GB athletes and medallists from the rest of the world. The main findings were the very strong to moderate correlations between race time and start & turn times to 15 m for the majority of the events analysed. Although the strongest correlation was found for start time in men's 200 m backstroke, the majority of strong correlations within starts were for shorter events, and for longer events in turns. However, whilst male GB swimmers were on average slower starters than non-GB swimmers in all events, female GB swimmers were faster starters than their non-GB counterparts in four of the events included. Furthermore, for turns, GB male swimmers were on average slower than the non-GB swimmers in all events analysed. However, female GB swimmers were faster than the non-GB swimmers in 100 m butterfly and 200 m backstroke, yet slower in all other events. Consequently, as GB athletes did not always have slower start and turn times than other nations, the hypotheses cannot be fully accepted.

Strong correlations were found between race time and start time for four of the men's events. Three of these were found in 50 m events, and one in a 100 m event, further substantiating that a fast start is integral to successful sprint races (Hay, 1986; Cossor and Mason, 2001; Slawson *et al.*, 2013). Furthermore, every men's backstroke event had a strong correlation, accounting for three of the four strong correlations found for start time. The backstroke start is different to that of the other three strokes; athletes start in the water with their feet on the wall and hands grabbing a bar on the starting block. The subsequent push off from the wall requires excellent coordination and technique to arch the back and lift the hips sufficiently to avoid dragging the feet in the water (Maglischo, 2003; Takeda *et al.*, 2014). As a result of beginning at the water level, the backstroke start results in a much-reduced flight time compared to a standing dive from the block, and thus a reduced entry distance. Consequently, their underwater phase may be longer than athletes performing a track start.

Whilst no strong correlations were found between race time and start time for any women's events, all the women's freestyle events had a moderate correlation of 0.58. This is similar to the findings of Arellano *et al*. (1994); however, they found significant high correlations between race time and start time in all women's freestyle events (50 m: r = 0.90; 100 m: r = 0.62; 200 m: r = 0.69). The discrepancy in results compared to the present study may be due to the effect of the higher heterogeneity within the sample group of Arellano *et al*. (1994). For that study, all preliminary heats and finals were included for all nations competing at the Olympic Games. This is in contrast to the present study which included only the medallists from other nations, with no inclusion of heat swims, and therefore comprised a more homogenous group. Nevertheless, it can be inferred that a strong start is key for women's freestyle events. Furthermore, a significant negative correlation has been found between underwater time and start time in women's 200 m freestyle (r = -0.61) (Cossor and Mason, 2001). This relationship suggests that the underwater phase plays a significant role in ensuring success in the 200 m freestyle start.

A very strong correlation was found between race time and turn time for women's 200 m freestyle. Whereas the start appeared to be more important for sprint events, the turns are ostensibly more important for middle distance events. It is also of note that of the five strong or very strong correlations found for the turn data, four of them were for women's events. This may be particularly salient considering there were no strong or very strong correlations found for any women's events within the start data. This contrasts with the turns in men's events, in which there was only one strong correlation found, that for 200 m freestyle. As these are merely correlations and only within this particular population, definite conclusions cannot be drawn regarding the causal influence of start and turn times to race times. However, it could be inferred from these data that starts were more integral to success in men's events, and turns in women's events, for this particular cohort. As races are being won by ever-finer margins, it would seem prudent for coaches to ensure their athletes excel in these crucial race skills. Whilst it is necessary for all swimmers to be proficient in both skills regardless of gender, there may be a gender difference in the relative importance of each skill to success. Further research with a more contemporary cohort is required to ascertain this.

On average, clean swim speeds were higher from the non-GB athletes than those from GB athlete indicating that Great Britain swimmers are not as fast in the free-swimming part of the race when compared with the rest of the world. However, for all but two events (50 m freestyle and 100 m freestyle for the females) differences between GB and non-GB swimmers were less than 0.10 m/s for both sexes. Additionally, the data extracted for Great Britain include some athletes that did not win a medal, i.e., those that were the top British performers in that event but came 4th or lower in the final. Consequently, results may have differed if only including GB medallists. There did not seem to be a pattern for a larger discrepancy in any particular event, however there were some differences across genders in where the largest discrepancies lay. For example, for the male athletes, the largest difference occurred in 50 m freestyle, yet for the other two distances, the biggest difference was observed in butterfly events. Contrastingly, for the female swimmers, the largest discrepancy was found in freestyle for both 50 m and 100 m events. Given that clean swimming speeds were principally comparable between GB and non-GB nations, differences in starts and turn times could indicate areas on which to focus to improve performance.

Male swimmers were consistently faster at starting than female swimmers, regardless of nation. This finding echoes previous literature in which it was argued that men were better able to utilise their underwater phase than were women (Cossor and Mason, 2001). However, discrepancies did occur between GB athletes and non-GB athletes. Great British male swimmers were consistently slower to 15 m during starts than were the male non-GB athletes. There were bigger differences between the two nation groups in 50 m and 100 m events than for 200 m events; given that having a good start is crucial to sprint events, improvements in start times to 15 m could have key implications for GB's athletes. The biggest difference in start time to 15 m was found in 100 m butterfly (0.41 s). Additionally, male GB athletes' clean swim speeds were 0.06 m/s slower on average in 100 m butterfly than rest of non-GB swimmers. Butterfly has a high energy cost (Barbosa *et al.*, 2005) which will naturally increase with event distance. As such, it is crucial to maximise the use of underwater phases so as to minimise excess energy loss, given that it is faster and more economical to swim beneath the surface due to a decrease in wave drag (Lyttle *et al.*, 1998). If GB male athletes could improve start performance and maximise their underwater phases in butterfly events, it could mediate the effect of slower clean swim speeds and conserve energy for the rest of the race.

When assessing the average turn-out time, GB males were consistently slower than their non-GB counterparts. For 100 m events, with only one turn, this discrepancy was smallest in 100 m freestyle (0.01 s), and largest in 100 m butterfly (0.19 s). Coupled with slower start time and a slower clean swim speed in 100 m butterfly, this adds further to the aforementioned suggestion that the underwater phases of 100 m butterfly could be a valid area of improvement for GB male swimmers. Furthermore, for 200 m events, the largest discrepancy in average turn time was in backstroke (0.21 s). This pattern, of the biggest difference in times in butterfly for 100 m events and backstroke for 200 m events, was the same for start time. Clean swimming speeds for the GB males in these events were comparable to non-GB athletes, with a difference of only 0.05 $m{\cdot}s^{-1}$ for 200 m backstroke. Consequently, it can be inferred that athletes in this study may benefit from improvements to their underwater phases in these two events.

On average, female GB swimmers had faster turn-out times in 100 m butterfly and 200 m backstroke, with the best advantage observed in 200 m backstroke. However, female GB swimmers were slower to 15 m than their non-GB counterparts in all other events, with the biggest discrepancy observed in 100 m freestyle. It was demonstrated above that GB female swimmers are slower to 15 m off the start and have lower clean swim speeds than do the non-GB swimmers in 50 m and 100 m freestyle. There is evidently more free swimming within 100 m events than with 50 m events; however, by capitalising on the start and turn, swimmers may mitigate the disadvantage of slower clean swim speeds. Furthermore, given that there was a strong correlation found between race time and turn time to 15 m ($r = 0.70$), it naturally follows that GB female swimmers must use their turn to their advantage to be successful in this event. Consequently, this further reinforces that significant gains may be made if GB female swimmers make improvements in the underwater phases of their starts and turns.

To explore how turn-out times differed over the course of 200 m races, each turn-out to 15 m was assessed individually, as times to 15 m may decrease up to 6% from the first to the third turn (Thompson *et al.*, 2000; Veiga and Roig, 2016). In 200 m races overall, both GB and non-GB athletes tended to have the third turn as their slowest when assessing group means. However, this was not equivocally the case for all athletes. For 200 m backstroke, the final turn was the fastest compared to the previous two turns for 30% of all swimmers. This 30% comprised an equal number of GB and world athletes, and meant that 50% of the GB swimmers were fastest on their third turn. This is perhaps unexpected given that, on average, GB male swimmers were found to be slower to 15 m than their non-GB counterparts during turns in 200 m backstroke. However, this inconsistency may be explained by various factors. First, the first turn metric discussed comprises an average of all three turn times for all GB male athletes, and thus will be influenced by the inclusion of slower swimmers. Additionally, though many male non-GB swimmers were slower on their final turn, they were ostensibly faster at turning overall within 200 m backstroke than were the GB male swimmers. Given that overall race velocity in 200 m backstroke has been highly correlated with the velocity within the third turn (Chatard *et al.*, 2001), it would be advantageous for GB swimmers to optimise their final turn.

Within 200 m butterfly, only 13% of all swimmers had their shortest turn-out time on their final turn, none of whom were GB swimmers. This provides further clarity with regards to female GB butterfly performance. Given that the biggest inconsistency within 200 m events in average turn time to 15 m between GB female swimmers and non-GB swimmers was observed in butterfly, it is advantageous to investigate from where this inconsistency may arise. By assessing each turn individually, it is evident that the female GB swimmers took longer to get to 15 m as the races progressed. Indeed, all GB swimmers except one took progressively longer to get to 15 m with each turn. This trend may occur as a result of fatigue resulting from the high energy cost of performing butterfly over a longer distance. This would render the underwater phases of turns even more important, as swimming farther underwater will reduce the free-swimming element of the race. This may be difficult given that respiratory fatigue is also a key issue by this point in the race, with many swimmers (through preference or necessity) surfacing almost as soon as they can in order to breathe. Consequently, there is a trade-off between respiratory fatigue and musculoskeletal fatigue within the arms and shoulders.

Only one swimmer out of the entire cohort had their shortest time to 15 m on their final turn within 200 m freestyle. Further, 76% of the cohort's final turn-out was the slowest, with 56% taking progressively longer on each turn throughout the race. This is similar to the findings of Veiga and Roig (2016), who found that elite freestyle athletes could not maintain their previous underwater distance on their final turn, travelling half a metre less. This contrasts with the backstroke and butterfly athletes who maintained their underwater distance. Whilst the present study did not measure underwater distance, it can be inferred from the turn-out data that the non-GB athletes are getting slower with each turn. Consequently, if GB athletes can improve their turn technique and strategy, they may be able to gain an advantage over swimmers from other nations.

A limitation of the present chapter is that it was not possible to complete inferential statistics to assess differences between groups due to non-uniformity in variance and small sample sizes in some groups, as mentioned in section 4.3.2. However, the descriptive results of this study may indicate several implications. With the exception of two events for the female swimmers, clean swimming speeds were similar between GB and non-GB athletes. Consequently, where discrepancies in start and turn out times have been found, there may be potential for improvement in race time and thus an increase in performance. The underwater phase accounts for a large proportion of start and turn time, suggested to be up to 84% (Slawson *et al.*, 2013). As such, improvements in underwater kicking ability may be instrumental in ensuring improvements in start and turn performance. Though results from this study provide important context as to the overall performance of GB swimmers up to 2018, new and younger swimmers will continuously join the Programme. These swimmers will undoubtedly present a range of UDK performance; therefore, an assessment of their technique may enable identification of factors present in better skilled kickers that are absent in less skilled kickers.

4.5 Conclusion

This study aimed first to establish the presence of associations between final race times and commonly collected metrics denoting the skill components of races. It then aimed to determine how the performances within those skill components of the race differed between top-performing GB athletes and swimmers from the rest of the world. The findings provide some support for hypotheses one and two; however, whilst comparable, GB athletes had marginally slower clean swim speeds than did the non-GB athletes. Further, top-performing GB athletes were not unequivocally slower than were non-GB athletes, thereby refuting hypothesis three. As such, the hypotheses cannot be accepted.

Strong correlations were found between race time and start time for all men's backstroke events, as well as men's 50 m freestyle. On average, non-GB athletes had higher swim speeds than did GB athletes. GB male swimmers had on average, slower start times than their non-GB counterparts. Within turn times, GB male swimmers were consistently slower to 15 m than were the non-GB swimmers. The GB female swimmers had faster start times than their non-GB counterparts in four of the events analysed. Female GB swimmers were faster to 15 m during turns in 100 m butterfly and 200 m backstroke, yet slower in all other events.

Overall, it was determined that within backstroke, butterfly, and freestyle, start times to 15 m are more highly correlated to final race time in shorter events than longer ones, and vice versa for turn times to 15 m. Further, there are several areas within the skill components of these races that present improvement opportunities for GB athletes, that could potentially result in podium success on the world stage.

CHAPTER FIVE

Determining Intra-cyclic Speed in Underwater Dolphin Kick: A Comparison of Two Methods

CHAPTER 5

Determining Intra-cyclic Speed in Underwater Dolphin Kick: A Comparison of Two Methods

5.1. Introduction

Biomechanical analysis is frequently used as part of an interdisciplinary strategy to improve both efficiency and skill mechanics within swimming (Mooney *et al.*, 2015). This often takes the form of video capture, with either two- or three-dimensional (2D or 3D respectively) systems used to collect kinematic information to analyse start, turn and swimming stroke mechanics. Of the extant body of knowledge regarding swimming, a considerable number of studies have utilised 2D video-based analysis (Seifert *et al*. 2007; von Loebbecke *et al.*, 2009a; de Jesus *et al.*, 2013; Veiga *et al.*, 2013; Atkison *et al.*, 2014; Connaboy *et al.*, 2016; Phillips *et al.*, 2021). This choice reflects the fact that 2D analysis is less time-consuming than 3D analysis in terms of data collection, processing, and analysis, allowing more rapid feedback of results to the athlete and coach. However, this efficiency can come at a cost, particularly in terms of accuracy and ecological validity. For example, researchers who employ 2D analysis do so on the assumption that the movement in question is planar, that is, the limb movements under evaluation are confined to a single, pre-defined plane. However, human movement is rarely two dimensional, and as a result, any measurements taken from outside this plane may be subject to large perspective errors (Payton and Hudson, 2017).

The limitations arising from 2D analysis are mostly rectified with the use of 3D video-based analysis. By removing the presence of perspective error, and enabling an investigation into the angular kinematics of the body, an accurate quantification of the performer's exact spatial movements can be provided (Payton and Hudson, 2017). However, this approach is not without its limitations; it is more expensive, both in terms of equipment and time (Barbosa *et al.*, 2011; Payton and Hudson, 2017). More cameras and associated systems are required and the set-up time is also much greater than with 2D analysis, which can cause considerable logistical issues with scheduling access to locations and participants. The time required to digitise and track the displacement of anatomical markers also vastly increases, resulting in a considerably longer post-processing and analysis time (Mooney *et al*., 2015). Furthermore, the interpretation of 3D data, particularly 3D angles, can be far more challenging than for angles derived from 2D analysis.

Within swimming, a key performance indicator is often swimming speed; as such, it is vital that researchers and practitioners are able to measure a performer's mean and instantaneous speed with a high level of accuracy. Instantaneous speed of a swimmer's centre of mass has previously been determined via both 2D and 3D video-based analysis (Atkison *et al*., 2014; Gavilan *et* al., 2006; Higgs *et al*., 2017; Matsuda *et al*., 2021). However, this process necessitates a multi-segmental model of the swimmer to be defined and digitised. Whilst this approach to measuring speed is appropriate within academic research, it is not practical in an applied coaching environment where rapid feedback is often required. As such, it can be difficult to regularly and accurately monitor a swimmer's improvements in underwater speed. Velocity-meters offer a practical alternative, as a quick and affordable way of assessing the horizontal speed of a swimmer. Velocity-meters, (also known as speedometers, 'swim-meters', or tethered velocity-meters) often comprise a thin, lightweight line and a rotary encoder. The line is connected to the swimmer either around the waist or via a collar, and is then wound around a reel that is connected to the rotary encoder (Phillips *et al*., 2021). In this way, it is purported that an accurate depiction of the swimmer's horizontal speed-time history can be provided. Despite their prevalence within the applied and research environment, (Craig and Pendergast, 1979; Schnitzler *et al*., 2010; Stamm *et al*., 2011, 2013; Phillips *et al*., 2014, 2021) there is a relative dearth of research investigating the validity or reliability of such devices.

Barbosa *et al*. (2011) assessed intra-cyclic velocity variation during land-based locomotion at a variety of self-paced speeds, from slow walking to maximal running. Velocity measures were collected both from a videometric system, and an integrated speedometer system, comprising commercially-available hardware alongside custom-built software (Barbosa *et al*., 2011). Participants completed seven trials of walking at the various speeds, with the velocity-meter connected via the hip. Trials were simultaneously recorded with a single camera in the sagittal plane; both systems sampled at 50 Hz. Following data collection, the hip was manually digitised over one gait cycle in each trial. The maximal velocity in the gait cycle was determined;

additionally, as a measure of intra-cyclic speed fluctuation, the coefficient of variation (CV) of the velocity in the gait cycle was calculated. Subsequently, to validate the speedometer system, the authors performed: paired Student's t-tests; linear regression models; and Bland-Altman plots. The authors noted no significant difference between systems, and "high associations" for both maximal velocity and CV data (R^2 =0.87 and R^2 = 0.97 respectively). Additionally, the authors stated that "more than 80% of the Bland-Altman plots were within the 1.96 standard-deviation criterion" (Barbosa *et al*., 2011:834). Consequently, it was concluded that the speedometer system was successfully validated.

Similarly, Feitosa *et al*. (2013) used the same system to compare intra-cyclic velocity variation during 25 m bouts of maximal butterfly and breaststroke. Participants swam two trials with the velocity-meter attached at the hip; again, both systems sampled data at 50 Hz. The maximum and minimum velocities during the stroke cycle were extracted, and the differences between them were calculated; additionally, CVs were also calculated. The same statistical tests were completed as in Barbosa *et al*., (2011). No significant differences were found for maximal velocity, minimal velocity, or the difference between the two; however, there were significant differences between CVs of the two systems. Linear regression models demonstrated "high associations" for maximal velocity (R^2 =0.98), minimal velocity (R^2 = 0.99), difference between maximal and minimal velocity (R^2 =0.99), and CV (R^2 =0.95). Further, the authors also stated that "more than 80% of the Bland-Altman plots were within the 1.96 standard-deviation criterion", and that the system was thus validated within butterfly and breaststroke (Feitosa *et al*., 2013).

Whilst a common approach in comparing two methods of measurement, the use of the above tests may be inappropriate. Inferential statistical tests designed for assessing the presence of significant differences or relationships are not valid for determining if two methods are in agreement (McLaughlin, 2013; Mundy *et al*., 2016). A non-significant difference does not indicate acceptable agreement, and it is likely that two such methods would demonstrate a significant relationship as they are purporting to measure the same thing (McLaughlin, 2013). Further, a significant correlation denotes the strength of the relationship between variables, not the agreement between them (Bland and Altman, 1986). In the present context, agreement refers to the extent to which speed measures from a velocity-meter are likely to differ from those derived from 3D video analysis. Importantly, if this difference would not cause issues in clinical or practical interpretation, it is suggested the two methods can be used interchangeably (Altman & Bland, 1983; Bland & Altman, 1986, 1999). In addition, the tests performed by previous authors were not accompanied by any direct measure of absolute or relative differences, rendering it difficult to form reliable conclusions regarding the ability of a velocity-meter to make accurate measurements.

Due to the aforementioned limitations of previous studies, it remains pertinent to appropriately investigate a velocity-meter against an established criterion method of measurement. Velocity-meter systems are being employed within high-performance swimming environments more frequently than ever. These devices are used for various applications, from assessment of underwater performance and streamline ability, to suit testing and selection. Consequently, the data from these systems are being incorporated by coaches and support staff into their evidence-based decision-making processes. As such, it is important to have full confidence in the data being provided. This may be achieved by comparing the speed values given by a velocity-meter with the centre of mass (COM) velocity of the swimmer, as the COM provides the most accurate understanding of the true movement pattern of the whole swimmer (Mason *et al*., 1989). Although the COM can be determined via 2D analysis, it would be difficult to ascertain whether differences in speed measures between the two systems were due to the velocity-meter's inaccuracy, or to the perspective error that is inevitable in a 2D analysis. As such, 3D analysis enables a much more accurate measure of COM kinematics. However, it is also important to note that velocity-meter lines are usually attached around the hips, thus ostensibly providing an indication of the speed of the hips. Given that the COM will not necessarily move synchronously with the hips throughout a stroke cycle, it is also important to compare the speed provided by a velocity-meter to that of the mid-point of the hips. Measurements between the SpeedReel and the COM may not agree because of the discrepancies from comparing a fixed point (the hips) to a point that may vary throughout the kick cycle. This may be attenuated by comparing SpeedReel to the mid-hip speed.

5.1.1 Aims

The aims of this study were:

1. To assess the agreement between speed measures from a custom-built velocity-meter (SpeedReel) and COM speed as provided by 3D video analysis during the underwater dolphin kick (UDK).
2. To assess the agreement between velocity-meter speed measures and mid-hip speed as provided by 3D video analysis during the UDK.
3. To provide guidelines for future users of the SpeedReel to facilitate appropriate use in a practical setting.

5.1.2 Hypotheses

It was hypothesised that:

1. The agreement between SpeedReel speed and COM speed would be unacceptable for all metrics measured.
2. The agreement between SpeedReel speed and mid-hip speed would be acceptable for all metrics measured.

5.2 Methods

See Chapter Three - General Methods for equipment details, test protocol, and data processing.

5.2.1 Participant information

Thirteen swimmers, nine national (six male and three female, mean FINA points: 813) and four international (three male and one female, mean FINA points: 932) level, (means ± SD: age: 25 ± 2 years; body mass: 77.7 ± 11.0 kg; height: 183.7 ± 6.1 cm) were recruited for this study. Based upon a recent performance classification system, with the aim of standardising results in swimming research, the performance level of the cohort ranged from 1 to 2 (Ruiz-Navarro *et al.*, 2022). Further, of the four international athletes, three were Olympians. Participants were free from injury, and specifically had no incidence of injury over the past year. Furthermore, participants were fully informed of all protocols and potential risks, via written and verbal explanation, and subsequently provided their written consent. Approval from the University Ethics Committee was obtained prior to any procedures.

5.2.2 Velocity-meter data collection

A bespoke velocity-meter known as the SpeedReel was used as a direct measure of the swimmer's speed; this device was designed and constructed by the Performance Sport Engineering department at the University of Southampton (Figure 5.1). The unit can be mounted to the side of the pool, and has within it an encoder that measures how fast the line is being pulled out, which is purported to correspond to the speed of the swimmer. The SpeedReel was securely fixed via a custom-made clamp at the static end of the pool, from which all trials commenced, proximate to the starting block in lane 4. Due to the focus on the underwater phase, the line was guided through a wall mounted pulley system set at a depth of 0.7 m. A thin cord was placed around the swimmer's waist, to which the SpeedReel line was attached, on to the side of the small of the swimmer's back, adjacent to where the SpeedReel was mounted. Through previous use within the National Centres, this placement has been anecdotally found to minimise the risk of the swimmer kicking the line as they swim.

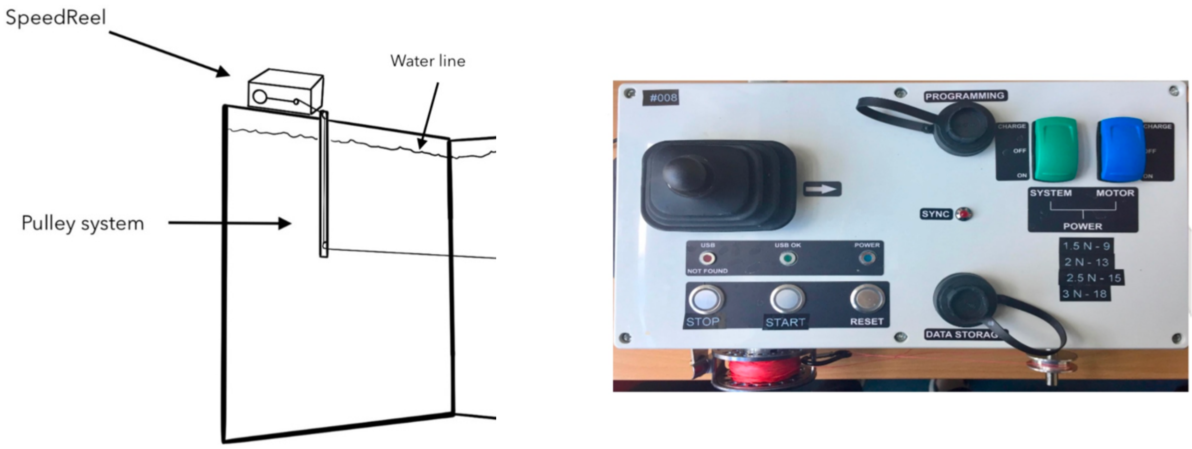


Figure 5.1. Diagrammatic representation of the SpeedReel and pulley system on poolside (left) (adapted from Phillips *et al*. (2020)) and photograph of the top of the SpeedReel (right).

Velocity data were captured at 250 Hz, and synchronised with the 3D video derived data post collection. In brief, the SpeedReel is programmed to emit an LED flash at 0.5 s, 1.5 s, and 2.5 s after the beginning of data acquisition. Obtaining the duration between the activation of the LED on the SpeedReel and the LED system in the pool allowed the synchronisation of the video and SpeedReel data. As different sampling frequencies were used to collect video and SpeedReel data (50 Hz and 250 Hz respectively), the video-derived data were resampled, within SIMI Motion, from 50 Hz to 250 Hz. The raw SpeedReel data were then filtered with a low pass 2nd order Butterworth filter, with the cut-off frequency set to 7 Hz.

5.2.3 Calculation of Variables

Following development of the 14-segment model, the magnitude of the COM resultant velocity (V_{COM}) was calculated until the swimmer left the volume, or reached the surface, whichever happened sooner.

$V_{COM} = [v_{COM\_X}^2 + v_{COM\_Y}^2 + v_{COM\_Z}^2]^{½}$

Additionally, the magnitude of the mid-hip velocity (V_{MIDHIP}) was also calculated over the total calibrated volume.

$v_{MIDHIP} = [((v_{Hipleft\_X} + v_{Hipright\_X})/2)^2 + ((v_{Hipleft\_Y} + v_{Hipright\_Y})/2)^2 + ((v_{Hipleft\_Z} + v_{Hipright\_Z})/2)^2]^{½}$

Both sets of data were exported into Microsoft Excel, where all further analysis was conducted. The COM speed and mid-hip speed data were time-synchronised to the SpeedReel (V_{REEL}) data as detailed above, allowing calculation of the variables below.

5.2.4 Definition of variables

The following variables were extracted from the COM, Mid-hip, and SpeedReel speed-time histories:

- **Mean overall speed** (mean speed over the synchronised sample of 3D and SpeedReel data, i.e., excluding initial wall push-off)
- **Maximum kick cycle speed** (mean of all the local speed maxima within the underwater phase)
- **Minimum kick cycle speed** (mean of all the local speed minima within the underwater phase)
- **Mean kick cycle intra-cyclic velocity variation (ICVV)** (mean of the ICVV values calculated for each kick cycle).

$$\mathrm{ICVV} = \left(\frac{(\text{max speed} - \text{min speed})}{\text{mean speed}}\right) * 100$$

5.2.5 Statistical Analysis

The following statistical procedures were completed between V_{COM} and SpeedReel speed, and then V_{MIDHIP} and SpeedReel speed. Root mean square error (RMSE) was first calculated to assess the goodness of fit between the 3D video-derived data and SpeedReel data. After data were checked for normality and homoscedasticity, 95% limits of agreement (LOA) were then calculated on mean overall speed, maximum kick cycle speed, and minimum kick cycle speed, using methods described by Bland and

Altman (Altman and Bland, 1983; Bland and Altman, 1986, 1999). The presence of proportional bias was assessed by determining if the slope of the least squares regression line of differences on averages differed significantly from 0 ($P<0.05$) (Ludbrook, 1997, 2010). Once it was ascertained that there was no proportional bias present for any of the three dependent variables, 95% confidence limits were calculated for the mean of the differences, and the upper and lower LOA. Consequently, fixed bias was considered to be present if the 95% confidence interval of the mean of the differences did not include 0 (Altman and Bland, 1983; Ludbrook, 1997). It was determined *a priori* that LOA would be unacceptable if their width was larger than the smallest worthwhile change (SWC) calculated from the SpeedReel speed. Smallest worthwhile change was calculated as 0.2 × between subject standard deviation (Hansen *et al*., 2011; Hopkins, 2004).

5.3 Results

An example of the three speed-time histories for a single trial is illustrated in Figure 5.2.

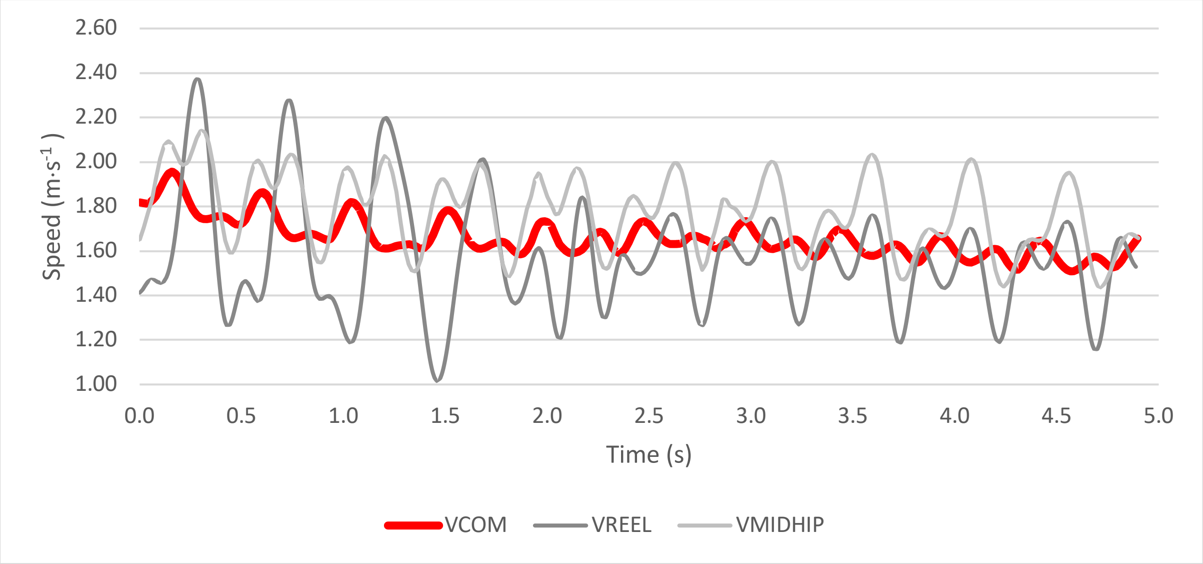


Figure 5.2. Synchronised speed time-histories of V_{COM}, V_{REEL}, and V_{MIDHIP} over one trial for one participant.

Table 5.1. Mean ± standard deviation mean overall speed, maximum kick cycle speed, minimum kick cycle speed, and ICVV for V_{COM}, V_{REEL}, and V_{MIDHIP}.

	Mean overall speed ($m \cdot s^{-1}$)	**Maximum kick cycle speed ($m \cdot s^{-1}$)**	**Minimum kick cycle speed ($m \cdot s^{-1}$)**	**ICVV (%)**
V_{COM}	1.66 ± 0.20	1.74 ± 0.19	1.60 ± 0.18	8 ± 2
V_{REEL}	1.59 ± 0.19	2.00 ± 0.16	1.17 ± 0.24	54 ± 19
V_{MIDHIP}	1.74 ± 0.21	1.89 ± 0.21	1.57 ± 0.19	19 ± 6

Table 5.2. Root mean square error values for the comparison between V_{COM} and V_{REEL}, and V_{MIDHIP} and V_{REEL}; RMSE denotes the goodness of fit between speed measures for each comparison. Values shown are the mean and range of RMSE values for each comparison.

	Mean RMSE ($m \cdot s^{-1}$)	**Range of RMSE ($m \cdot s^{-1}$)**
V_{COM}/ V_{REEL}	0.27	0.19 – 0.48
V_{MIDHIP}/ V_{REEL}	0.32	0.23 – 0.51

5.3.1 V_{REEL} versus V_{COM}

Some differences were observed between the mean overall speeds provided by the two methods, with the SpeedReel recording a lower mean overall speed than the video-based method for all participants (Table 5.1). On average, V_{REEL} overall mean speeds were 4% lower than those for V_{COM}. Differences were also found in the maximum kick cycle speeds provided by the two methods, with higher V_{REEL} maximum kick cycle speeds than those for V_{COM} for every participant. In contrast, the SpeedReel appeared to underestimate minimum speeds, as V_{REEL} minimum kick cycle speeds were consistently lower than for V_{COM} (27% mean difference).

Root mean square error values for the complete kicking trials ranged from 0.19 $m \cdot s^{-1}$ to 0.48 $m \cdot s^{-1}$, with a mean value of 0.27 $m \cdot s^{-1}$ (Table 5.2). The ICVV values were considerably greater for V_{REEL} values than for V_{COM}. Mean ICVV values were 54% for V_{REEL} compared to 8% for V_{COM}. The highest ICVV for the 3D-derived data was 12%; the highest ICVV for the SpeedReel data was 91% (Table 5.1).

Fixed bias was present for mean overall speed, maximum kick cycle speed, and minimum kick cycle speed. Limits of agreement were also unacceptable for all three dependent variables assessed. The LOA for mean overall speed were 0.07 ± 0.06 $m.s^{-1}$. The 95% confidence interval for the upper limit was 0.16 $m.s^{-1}$ to 0.10 $m.s^{-1}$; the 95% confidence interval for the lower limit was 0.05 $m.s^{-1}$ to -0.02 $m.s^{-1}$ (Table 5.3).

The LOA for maximum kick cycle speed were -0.26 ± 0.31 $m.s^{-1}$. The 95% confidence interval for the upper limit was 0.21 $m.s^{-1}$ to -0.12 $m.s^{-1}$; the 95% confidence interval for the lower limit was -0.41 $m.s^{-1}$ to -0.74 $m.s^{-1}$ (Table 5.4)

The LOA for minimum kick cycle speed were 0.43 ± 0.26 $m.s^{-1}$. The 95% confidence interval for the upper limit was 0.84 $m.s^{-1}$ to 0.55 $m.s^{-1}$; the 95% confidence interval for the lower limit was 0.31 $m.s^{-1}$ to 0.02 $m.s^{-1}$ (Table 5.5).

5.3.2 V_{REEL} versus V_{MIDHIP}

On average, mean overall V_{REEL} values were 9% lower than those for V_{MIDHIP} (Table 5.1). Similar to V_{COM}, the SpeedReel generally overestimated maximum kick cycle speed compared with the video-based method; there was a mean percentage difference of 5% between V_{REEL} and V_{MIDHIP}. However, whilst this was a consistent trend with V_{COM} across the entire cohort, the SpeedReel recorded lower values than did V_{MIDHIP} for five of the 13 participants. Additionally, the SpeedReel appeared to underestimate minimum speeds, as minimum kick cycle speeds were lower for V_{REEL} than for V_{MIDHIP} for all participants (25% mean difference).

Root mean square error values for the complete kicking trials ranged from 0.23 to 0.51 $m \cdot s^{-1}$, with a mean value of 0.32 $m \cdot s^{-1}$ (Table 5.2). Higher ICVV values were derived from the SpeedReel data than for V_{MIDHIP}; mean ICVV values were 19% for V_{MIDHIP}. Further, the highest ICVV for the 3D-derived data was 31%. Consequently, the SpeedReel overestimated ICVV compared with both V_{COM} and V_{MIDHIP}. On average,

V_{REEL} ICVV values were 65% higher than those for V_{MIDHIP}, and 85% higher than those for V_{COM} (Table 5.1).

Fixed bias was present for mean overall speed and minimum kick cycle speed, but was absent for maximum kick cycle speed. Limits of agreement were unacceptable for all three dependent variables assessed. The LOA for mean overall speed were 0.15 ± 0.08 $m.s^{-1}$. The 95% confidence interval for the upper limit was 0.28 $m.s^{-1}$ to 0.19 $m.s^{-1}$; the 95% confidence interval for the lower limit was 0.12 $m.s^{-1}$ to 0.03 $m.s^{-1}$ (Table 5.3).

The LOA for maximum kick cycle speed were -0.10 ± 0.39 $m.s^{-1}$. The 95% confidence interval for the upper limit was 0.49 $m.s^{-1}$ to 0.08 $m.s^{-1}$; the 95% confidence interval for the lower limit was -0.29 $m.s^{-1}$ to -0.70 $m.s^{-1}$ (Table 5.4).

The LOA for minimum kick cycle speed were 0.40 ± 0.31 $m.s^{-1}$. The 95% confidence interval for the upper limit was 0.88 $m.s^{-1}$ to 0.54 $m.s^{-1}$; the 95% confidence interval for the lower limit was 0.25 $m.s^{-1}$ to -0.08 $m.s^{-1}$ (Table 5.3).

Table 5.3. Mean difference and 95% limits of agreements with corresponding confidence intervals, and SWC values, for the comparison between V_{COM} and V_{REEL}, and V_{MIDHIP} and V_{REEL}, for mean overall speed, maximum kick cycle speed, and minimum kick cycle speed.

		Mean difference	95 % CI	Lower limit	95% CI	Upper limit	95% CI	SWC
Mean overall speed ($m.s^{-1}$)	**V_{COM}/V_{REEL}**	0.07	[0.06 – 0.09]	0.01	[-0.02 – 0.05]	0.13	[0.10 – 0.16]	0.04
	V_{MIDHIP}/V_{REEL}	0.15	[0.13 – 0.18]	0.07	[0.03 – 0.12]	0.24	[0.19 – 0.28]	0.04
Maximum kick cycle speed ($m.s^{-1}$)	**V_{COM}/V_{REEL}**	-0.26	[-0.36 – -0.17]	-0.57	[-0.74– -0.41]	0.05	[-0.12 – 0.21]	0.03
	V_{MIDHIP}/V_{REEL}	-0.10	[-0.22 – 0.01]	-0.49	[0.08 – 0.49]	0.28	[-0.70 – -0.29]	0.03
Minimum kick cycle speed ($m.s^{-1}$)	**V_{COM}/V_{REEL}**	0.43	[0.35 – 0.51]	0.17	[0.02 – 0.31]	0.69	[0.55 – 0.84]	0.05
	V_{MIDHIP}/V_{REEL}	0.40	[0.30 – 0.49]	0.09	[-0.08 – 0.25]	0.71	[0.54 – 0.88]	0.05

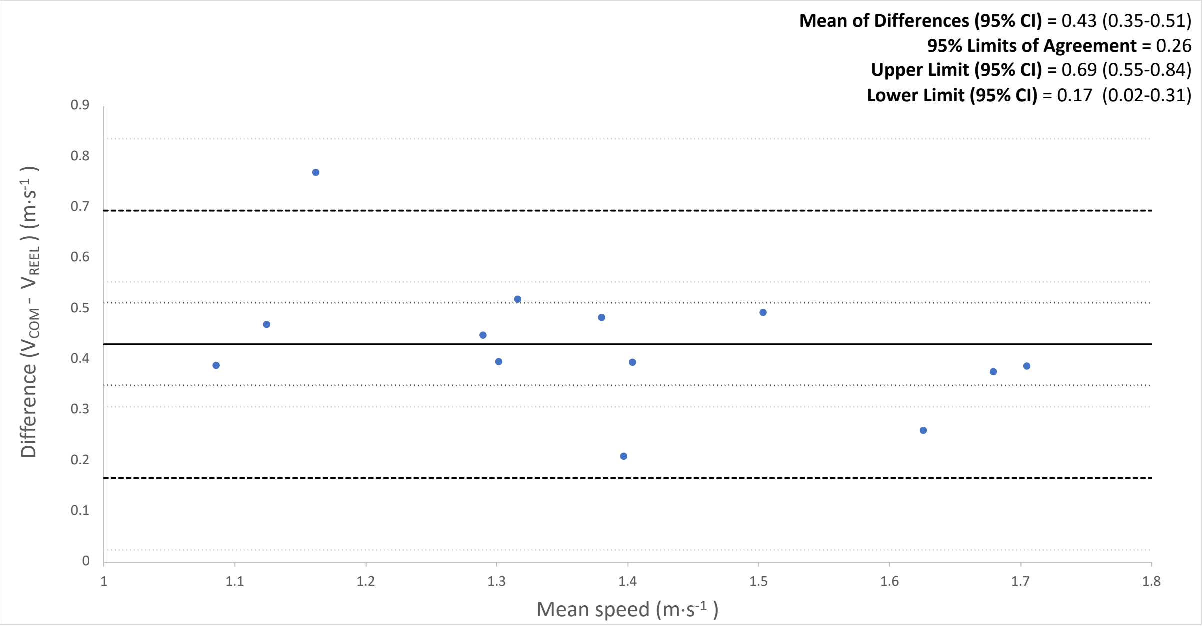


Figure 5.3. Example Bland-Altman plot demonstrating the mean of differences and LOA for minimum kick cycle speed. Black solid line represents the mean of differences, black dashed lines represent the upper and lower LOA; dark grey dotted lines represent the 95% confidence intervals for the mean of differences; light grey dotted lines represent the 95% confidence intervals for the upper and lower LOA.

5.4 Discussion

5.4.1 V_{REEL} versus V_{COM}

The mean overall speeds provided by the two systems are similar, with only 0.07 m.s^{-1} difference in mean overall speed across all participants. However, a lower mean overall speed was found for the V_{REEL} than for V_{COM} for every participant. This trend shows that the SpeedReel has a tendency to underestimate mean speed during UDK when compared with a criterion method. This pattern of lower V_{REEL} values than V_{COM} was also found for minimum kick cycle speed; however, the divergence between the two systems was much greater, with a 27% mean difference. The consistent difference between the systems across the entire cohort suggests a presence of systematic bias; however, this bias was not consistently in the same direction across all variables. The opposite trend was found for maximum kick cycle speed; SpeedReel values were higher than V_{COM} values for every participant. Consequently, the SpeedReel is likely over- and under-estimating peaks and troughs respectively over each kick cycle.

Root mean squared error was calculated as a measure of reliability, via the determination of ‘goodness of fit’ between outputs from the two systems (O’Donoghue, 2012). Root mean squared error values demonstrated a considerable range; however, all RMSE values were below 0.50 m.s^{-1}. The mean RMSE value was 0.27 m.s^{-1}, with a standard deviation of 0.08 m.s^{-1}. As such, this could indicate fair reliability, particularly as there was not much variation around the mean. However, this is still a potential discrepancy of 0.27 m.s^{-1} on average between systems; thus, it is necessary to consider other metrics alongside RMSE.

Limits of agreement were found to be unacceptable for all three dependent variables, as their width was larger than the SWC. In brief, the SWC denotes the smallest enhancement required to result in an improved athletic performance (Anderson *et al.*,2006; Hansen *et al.*, 2011; Hopkins *et al.*, 1999). If noise or error within a test is greater than the SWC, any improvement in performance must be greater than that noise in order to conclude that the improvement is genuine rather than as a result of error (Hansen *et al.*, 2011). The width of the LOA for all three dependent variables was larger than the SWC; consequently, if a practitioner measures any of these variables with the SpeedReel, they could not be certain whether changes in those variables were true performance changes, or if they are as a result of equipment error. However, the extent to which the width of the LOA differed from the SWC varied across the three variables. The largest discrepancy was found for maximum kick cycle speed, as the SWC was found to be 0.03 m.s^{-1}, whereas the width of the LOA was 0.31 m.s^{-1}. Conversely, for mean overall speed, the width of the LOA is merely 0.02 m.s^{-1} greater than the SWC (0.06 m.s^{-1} and 0.04 m.s^{-1} respectively). As such, whilst LOA were found to be unacceptable for all three variables, mean overall speed could be measured with the SpeedReel providing users are cognisant of the potential slight underestimation in measurement.

Fixed bias was also present for all three dependent variables measured. The presence of fixed bias denotes that one set of measurements gives values that consistently differ from the other set (Ludbrook, 2010). For mean overall speed and minimum kick cycle speed, the SpeedReel recorded lower values than V_{COM} for all participants; however, the opposite was true for maximum kick cycle speed. Limits of agreement for mean overall speed were 0.07 ± 0.06 m.s^{-1}. This indicates a bias of 0.07 m.s^{-1}, and that, for a given measurement, the mean overall speed provided by the SpeedReel may be 0.13 m.s^{-1} above or 0.01 m.s^{-1} below that given by the 3D video data (Bland and Altman, 1986). Whilst LOA were unacceptable, the bias found is relatively small, particularly in comparison to that of the other two measures. Furthermore, the 95%

confidence intervals for the limits were fairly narrow. If these confidence intervals represent the range in which a new measurement from the same population would be expected to occur (Ludbrook, 2010), then it can be inferred that practitioners may be fairly confident in the speedreel's reliability to produce similar results for overall mean speed from multiple trials.

A more thorough inspection of the maximum and minimum kick cycle speeds is warranted. For the former, LOA were -0.26 ± 0.31 $m.s^{-1}$, indicating that for a given measurement, the SpeedReel may be 0.05 $m.s^{-1}$ above or -0.57 $m.s^{-1}$ below that of V_{COM}. The bias and LOA were even greater still for minimum kick cycle speed; LOA were 0.43 ± 0.26 $m.s^{-1}$, indicating that for a given measurement, the SpeedReel may be 0.69 $m.s^{-1}$ above or 0.17 $m.s^{-1}$ below that of V_{COM}. This provides further evidence to the suggestion that the SpeedReel overestimated and underestimated maximum kick cycle speed and minimum kick cycle speed, respectively, and to a much greater degree than the underestimation of mean overall speed. Additionally, the 95% confidence intervals for the limits are much wider than those for mean overall speed. As such, even though the sample size is quite small, this indicates that there can be quite substantial differences between the two systems (Bland and Altman, 1986). In practical terms, swimming races are often won by hundredths of a second; a difference of nearly 0.5 $m.s^{-1}$ in measurement could therefore be problematic. As mentioned previously, when making performance decisions, it would be difficult to be certain whether a big change in performance was accurate or due to error from the SpeedReel. As such, the two systems cannot be used interchangeably, and it is not recommended to solely use the SpeedReel to measure and monitor either maximum or minimum kick cycle speeds within UDK.

There may be multiple causes of these discrepancies between the two systems. The underestimation of mean overall speed by the SpeedReel potentially suggests an issue with calibration in either or both systems. Though 3D-video analysis was used as the criterion method in this study, it is not inherently free of error; such inaccuracies may arise from erroneous reconstruction of control points, imprecise digitisation of markers, or poor video image quality (Payton and Hudson, 2017). As stated in Chapter Three of this thesis, reconstruction error and intra-rater reliability were considered acceptable. However, the RMSE values for the toe markers were slightly larger than for other markers and could have resulted in some error in the calculated centre of mass kinematics. Furthermore, the large differences in maximum and minimum speeds may be due to sources of random error in the data collection and processing itself. For example, though the line was placed so as to minimise the participant accidentally striking it, the oscillatory nature of the kicking action itself may have influenced the movement of the line over the underwater phase. Additionally, the degree of smoothing and the chosen cut-off frequencies can have an effect on the maxima and minima values.

Irrespective of the systematic and random errors inherent in both systems, it is inevitable that the speed data collected from the two systems will still have some differences as the direction of the velocities from the systems will not be aligned. The direction of the velocity from the SpeedReel will inevitably be along the direction of the line, which dependent on various factors. These include the depth at which the line is guided through to be connected to the swimmer, and the path that the swimmer ultimately follows through the water. The 3D video-derived velocity data comprise absolute velocity, and thus include a vertical velocity component that is unlikely to be represented in the SpeedReel data. This is important context that does not invalidate the present study, as the aim was not to replace 3D video analysis with the SpeedReel, but to see if they could be used interchangeably in applied practice conditions to monitor instantaneous speed.

It is difficult to compare the present LOA results with those from previous investigations, due to discrepancies in how this analysis method was used. Both the Barbosa *et al*. (2011) and Feitosa *et al*. (2013) studies simply reported that “more than 80% of the Bland-Altman plots were within the 1.96 standard-deviation criterion”. Whilst the use of ‘Bland-Altman’ plots as the main analysis has become a common misconception in the employment of LOA, the plots alone do not constitute the analysis, and instead are predominantly an assumption check (Bland and Altman, 2003; Mansournia *et al*., 2021; Mundy and Clarke, 2019). Given that these authors did not provide further analysis or information, a direct comparison between their results and the present results is not possible.

Intra-cyclic velocity variation was calculated for the data from both systems, to determine if a difference occurred in the assessment of energy cost. Intra-cyclic velocity variation is a metric often used to denote efficiency within swimming, with a lower ICVV denoted as indicating a higher swimming efficiency (Barbosa et al., 2008).

Differences existed between ICVV outputs between the two systems. The SpeedReel-derived ICVVs were higher for each participant than those obtained from the COM 3D data, with a difference between the systems of 46% (Table 5.1). The discrepancies in ICVV values result from the overestimation of maximum speeds and underestimation of the minimum speeds recorded by the SpeedReel. These discrepancies in maxima and minima between systems may be because the SpeedReel measures the swimmer's speed at the point of attachment, in this case the hip, whereas the location of the centre of mass will likely shift along the swimmer's body throughout the kick cycle, and will not move synchronously with the hips. Comparisons have been made between the velocity variations of the COM versus those of the hip, and authors have found that the two points tend to be out-of-phase with each other, and that the maximal and minimal velocities of the hip are larger and smaller, respectively, than those of the COM (Mason et al, 1989; Gourgoulis et al., 2018).

5.4.2 V_{REEL} versus V_{MIDHIP}

All participants recorded a higher mean trial speed for V_{MIDHIP} than for V_{REEL}. The mean percentage difference of 9% was greater than that found between V_{REEL} and V_{COM}. This is an interesting and unexpected finding as it was hypothesised that the V_{MIDHIP} data would be more closely related to the SpeedReel than would the V_{COM}, due to the mid-point of the hips being the closest to the point of attachment of the SpeedReel. Additionally, all minimum kick cycle speeds were higher for V_{MIDHIP} than for the SpeedReel; as such, even when undertaking an arguably more analogous analysis, it appears the SpeedReel still underestimates mean overall speed and minimum kick cycle speed. In contrast, whilst the SpeedReel generally overestimated maximum kick cycle speed, no consistent trend was found, with five of the 13 participants recording a higher maximum kick cycle speed for V_{MIDHIP} than for the SpeedReel. Furthermore, the differences between mean values for both maximum and minimum kick cycle speeds were smaller than those for V_{COM}, which aligns more closely with the hypothesis.

The range of RMSE values for V_{MIDHIP} were similar to those for V_{COM}. However, RMSE values for V_{MIDHIP} were equal to or higher than those for V_{COM} for all of the participants, resulting in a higher average RMSE value for mid-hip (Table 5.2). Again, this was unexpected; nevertheless, only one of the RMSE values for V_{MIDHIP} was above 0.50

$m.s^{-1}$ and, despite the higher mean value, the standard deviation was smaller than for the V_{COM} values. As such, like the V_{COM} data, adequate reliability could be inferred. Limits of agreement were found to be unacceptable for all three dependent variables assessed. Additionally, the greatest discrepancy between the SWC and the width of the LOA was again found for maximum kick cycle speed; 0.03 $m.s^{-1}$ and 0.39 $m.s^{-1}$ respectively. However, whilst the mean difference between SpeedReel and V_{MIDHIP} was -0.10 $m.s^{-1}$, no fixed bias was found for maximum kick cycle speed. In contrast to the SpeedReel consistently overestimating this metric compared with V_{COM}, eight of the 13 participants recorded a lower maximum kick cycle speed with the SpeedReel than with V_{MIDHIP}. Furthermore, maximum kick cycle speed had the widest limits of the three variables, with concomitantly widest 95% confidence intervals for those limits. As such, it could be concluded that, although there is a lack of systematic error, the measurement of maximum kick cycle speed with the SpeedReel is accompanied by a considerable amount of random error (Atkinson and Nevil, 1998). Further due to the wide confidence intervals, there is a decreased possibility of precise population estimates. In this context, this means that the maximum kick cycle speed from this sample is likely to be different from that in the population (Field, 2009), and therefore is not accurate.

Fixed bias was found to be present for both mean overall speed and minimum kick cycle speed, as the SpeedReel consistently overestimated both of these metrics. Additionally, for minimum kick cycle speed, the discrepancy between the width of the LOA and the SWC was of a similar magnitude to that of maximum kick cycle speed, with similarly wide 95% confidence intervals for the limits. However, in a comparable manner to the V_{COM} comparison, the width of the LOA for mean overall speed was only 0.04 $m.s^{-1}$ larger than the SWC (0.04 $m.s^{-1}$ and 0.08 $m.s^{-1}$ respectively). This would again suggest that more confidence could be placed in measurements of mean overall speed, than of the other two metrics. However, the extent to which the LOA differed from the SWC was greater for all three V_{MIDHIP} variables than for the three V_{COM} variables. This was unexpected, due to the hypothesis that V_{MIDHIP} measures would show better agreement with those from the SpeedReel than would the V_{COM} measures. In contrast, this finding demonstrates that even when the SpeedReel is compared with a fixed point closest to the point of attachment, there is still a degree of error that could render measurements invalid.

Intra-cyclic velocity variations were lower on average for V_{MIDHIP} than for the SpeedReel data: 19% and 54% respectively. This discrepancy can, again, be explained by the wide variance in speed within the SpeedReel data that is not present in the V_{MIDHIP} data. However, the mean ICVV for V_{MIDHIP} was more than twice that of V_{COM} (19% and 8% respectively). This further illustrates that the COM and the mid-point of the hips are not always the same point along the body, and that, on average, the hips experience a greater variation in velocity both within and between cycles than does the COM. In addition, when examining the individual ICVV values, the participant who had the lowest ICVV for V_{MIDHIP} (9%), also had the highest ICVV for the SpeedReel data (91%). This provides a further example of how false conclusions may be drawn regarding an athlete's variation intra-cyclic speed, if the SpeedReel data alone are considered.

5.4.3 Guidelines for SpeedReel Use in Applied Settings

The third aim of this chapter was to develop guidelines for SpeedReel users, to facilitate appropriate and accurate use in a practical setting. Cognisant to the potential limitations of the SpeedReel illustrated above, it is possible to provide associated recommendations for best practice.

Due to the small margin between the width of the LOA and the SWC for mean overall trial speed, it was established that the SpeedReel may provide a more adequate measurement of this metric than the others assessed in this study. Nevertheless, the SpeedReel did underestimate mean overall speed for all participants. As mentioned above, this suggests a possible issue with the SpeedReel's calibration. Consequently, care should still be taken when using the SpeedReel to measure mean overall speed, particularly between participants when the extent of the underestimation may differ across a cohort. The SpeedReel also underestimated minimum kick cycle speed, and to a greater degree than it did mean overall speed. This gave the impression that each participant was decelerating more than their true change in speed, over each kick cycle. As such, it is not recommended that the SpeedReel solely be used to monitor minimum kick cycle speed between participants. For maximum kick cycle speed, in contrast, the SpeedReel overestimated values; this overestimation was consistent for the comparison with V_{COM} and for the majority of the cohort for the comparison with V_{MIDHIP}. As such, practitioners could falsely infer that athletes were reaching higher velocities than in actuality over each kick cycle. However, this would not be uniform across every participant if comparing to velocity of the mid-point of the hips. Consequently, it is recommended that the SpeedReel not be used to measure and monitor maximum kick cycle speed between or within participants, due to the possibility of non-uniform bias.

Alongside mean overall speed, measures of kick frequency may also be taken with the SpeedReel, as well as time spent above and below mean speed. Measurements of maximum and minimum values, as well as kick amplitude, are not recommended, due to the aforementioned overestimation of peaks and troughs present in the SpeedReel data. Another metric that coaches or practitioners may be interested in is efficiency over the underwater phase. It was determined that measurements of ICVV using the SpeedReel, as an indication of efficiency, may be inaccurate and misleading. This was due to large variation around the mean causing overestimated peaks and troughs in the SpeedReel data. Consequently, the measurement and monitoring of ICVV with the SpeedReel is not recommended.

5.5 Conclusion

The aim of this study was to determine how speed values obtained via a custom-built velocity-meter compared with those from an established criterion method. It was first hypothesised that the agreement between V_{REEL} and V_{COM} would not be acceptable for any of the metrics assessed, namely mean overall speed, and maximum and minimum kick cycle speeds; this hypothesis was accepted. The second hypothesis was that agreement between V_{REEL} and V_{MIDHIP} would be acceptable for all metrics assessed. However, bias was present for both mean overall speed and minimum kick cycle speed, and LOA were unacceptable for all metrics. Consequently, this hypothesis was rejected.

It was found that mean overall speeds were similar when comparing SpeedReel to V_{COM} and V_{MIDHIP}, yet the SpeedReel has the tendency to underestimate mean overall speed. As such, it was concluded that the SpeedReel could be used to measure and monitor mean overall speed, but with cognisance to the slight potential underestimation that may occur. In contrast, it was recommended that the SpeedReel not solely be used to monitor maximum or minimum kick cycle speeds. As ever, data collection, processing, and analysis procedures should always be conducted with the utmost rigour and care to reduce the possibility of measurement error. Furthermore, performance decisions ought to be based on a holistic approach with a variety of appropriate data, rather than a single measurement tool. Additionally, the sample size within this study was relatively small, potentially limiting its power and ability to be extrapolated to a wider population. However, this chapter has demonstrated that there are ways in which a velocity-meter can be used accurately within the swimming environment. As such, if used appropriately, the SpeedReel can be a beneficial and convenient resource in swimming research and performance interventions.

CHAPTER SIX

Kinematic Comparison of Prone and Supine Underwater Dolphin Kicking

CHAPTER SIX

Kinematic Comparison of Prone and Supine Underwater Dolphin Kicking

6.1. Introduction

With respect to the naturally adept swimming technique of marine mammals, human undulatory underwater swimming is comparatively slower and less efficient (Connaboy *et al*., 2009). Comparisons of kinematic measures from Olympic swimmers and cetaceans have been made (Von Loebbecke *et al*. (2009 [b]). Kick frequency and amplitude were relatively constant across the range of velocities measured, which contrasted with cetaceans' technique of increasing kick frequency with increasing velocity (Rohr & Fish, 1994; Von Loebbecke *et al*., 2009 [b]). In addition, underwater dolphin kick (UDK) speeds demonstrated by the human swimmers were around three times slower than those of cetaceans; however, both groups displayed similar kick and non-dimensional amplitudes. Thus, a higher frequency was required of a human swimmer to achieve the same swimming speed as the cetaceans. Accordingly, Strouhal numbers for humans were three times larger and more variable than for cetaceans (Von Loebbecke *et al*. (2009 [a]). Strouhal number is a dimensionless number describing the nature of oscillating flow, and is related to the frequency of vortex shedding; in particular, how fast vortices are being shed and the space between them (von Loebbecke *et al*., 2009 [b]). Strouhal number is often used as a measure of propulsive efficiency as it indicates the relative ease or difficulty an animal has in travelling through a fluid. Optimal propulsive efficiency is thought to fall between a narrow range of Strouhal numbers, 0.2 to 0.4 (Taylor et al., 2003). Dolphins and other cetaceans have been found to swim within this range (Rhor and Fish, 2004), however mean Strouhal number for human swimmers has been reported as 0.80 (von Loebbecke et al., 2009 [a]). Much of the discrepancies in technique between the two groups is attributed to the humans' relative anatomical constraints compared with marine mammals. These constraints include a comparatively low range of motion in the knees and ankles, alongside a smaller available surface area to produce vortices of equal size and power from both phases of the kick (Von Loebbecke *et al*. (2009 [b]).

Despite the anatomical restrictions limiting human performance in UDK, it is important to ensure as much kick symmetry between kick phases as possible to maximise equal propulsion in both phases (Atkison *et al*., 2014). The two phases of UDK are most commonly referred to as the upkick and downkick. Within prone UDK, downkick is the first phase within the kick cycle, and is denoted by hip flexion, knee extension, and dorsi-flexion. The upkick is the second phase of the kick cycle, and is characterised by hip extension, knee flexion, and plantar-flexion. As much of the current literature on UDK has been completed prone, references to the upkick and downkick always refer to the same movements from the lower limbs. However, in supine UDK, the upkick is the first phase of the kick cycle, (characterised by hip flexion, knee extension, and dorsi-flexion) and the downkick is the second phase (denoted by hip extension, knee flexion, and plantar-flexion). Consequently, referring to the phases solely as upkick and downkick may engender confusion if discussing both kicking orientations. In both orientations, the first and second phase of the kick cycle comprise the same movements from the three joints. Of the three joint actions involved, the flexion and extension of the knee is the most identifiable throughout the cycle. Consequently, when directly comparing prone and supine UDK the two phases could be referred to as knee extension and knee flexion phase, to avoid confusion inherent in referring to up or down motion. As such, unless otherwise stated, this convention is followed in the remainder of this thesis.

Symmetry between knee flexion and extension phases has been investigated via the comparison of joint angles, horizontal centre of mass velocity and displacement, amplitude, frequency, and vertical toe velocities (Atkison *et al*., 2014). The authors posited that swimmers who are more able to actively upkick appear to be fastest at UDK. It was suggested that this may be achieved by ensuring comparable maximum vertical toe velocities in both phases of the kick, thereby generating similar propulsion during the downkick and the upkick. The high correlation found between UDK speed and maximum vertical toe velocity in the knee flexion phase is in agreement with the findings of Higgs *et al*. (2017) who found maximum vertical toe velocity to be a strong predictor of UDK performance. Relative amount of time spent in the knee extension and knee flexion phases was also proposed as a critical temporal indicator of skilled underwater dolphin kick (UDK) (Atkison *et al*., 2014). Faster swimmers divided the time similarly between each phase, whereas slower swimmers spent comparatively longer in the knee flexion phase. This could be particularly disadvantageous if this is a predominantly resistive phase; less time for propulsion and more time experiencing drag over each kick cycle will inevitably reduce a swimmer’s speed over their underwater phase. The authors concluded that flexibility in the upper thoracic spine, knees, and ankles is important for successful UDK, alongside recommending limiting the duration of the upkick and ensuring high maximum toe velocities during this phase (Atkison *et al.*, 2014). Whilst this study offers some insight into the UDK, analysis was undertaken in two dimensions, not three, and the authors assumed bilateral symmetry. This may not be the case in UDK, and the participants likely also demonstrated movement medio-laterally that was not quantified.

In an attempt to quantify the symmetry of the human undulatory wave, Hochstein and Blickhan (2014) assessed the magnitude and distribution of the joint amplitudes along the swimming body with respect to the horizontal swimming direction. Ten swimmers performed maximum effort prone UDK; peak-to-peak joint amplitude was calculated and divided into dorsal and ventral components. These were assessed alongside hip, knee, and ankle joint angles, relative to the shoulder joint, of which the phase was set to zero. Total amplitude along the body was found to increase quadratically as it travelled caudally. Similarly to the findings of Atkison *et al.* (2014), time spent in the knee flexion phase was longer than in the knee extension phase. With respect to the dorsal and ventral symmetry of the joint peak-to-peak amplitudes, several asymmetries were observed, most prominently at the shoulder and knee. However, the movement of the end effector (i.e., the toes) was nearly symmetrical (Hochstein and Blickhan, 2014). It was suggested that, though humans are anatomically constrained in their ability to generate propulsion, this is compensated for by complex coordination that distributes these asymmetries in order to ensure a more symmetrical movement of the toes (Hochstein and Blickhan, 2014). This may be in part be due to a strategy in which decreases down the chain towards the end-point (in this case, the toes) to ensure a consistent performance outcome (Latash, 2010). Mean body wave velocity has been found to correlate strongly with UDK speed and it is suggested that for optimum UDK performance, athletes should ensure a fast segmental transfer of momentum caudally (Higgs *et al.*, 2017).

The symmetry between knee extension phase and knee flexion phase may be improved with enhancements to flexibility in the knees and ankles (Willems *et al.*, 2014; Chen *et al.*, 2022). The effect of ankle flexibility and strength on UDK speed and propelling efficiency has been investigated by comparing performance before and after applying tape to restrict mobility (Willems *et al.*, 2014; Shimojo *et al.*, 2019). UDK speed significantly decreased following tape application (Willems *et al*., 2014; Shimojo *et al*., 2019), denoted by a reduction in both active and passive plantar flexion (Willems *et al*., 2014). Additionally, kick frequency and kick distance per cycle were reduced in the taped condition (Willems *et al*., 2014). Greater maximum plantar flexion may be related to UDK performance (Sugimoto *et* al., 2008; Atkison *et al*., 2014). Consequently, this restriction in plantar flexion range could reduce the ability to powerfully upkick, which in turn will affect UDK speed.

Analysis of UDK has often involved the measurement and assessment of frequently collected kinematic variables. Commonly reported measures include joint centre amplitudes, joint angles, angular velocities and ranges of motion, and angle of attack (Connaboy et al., 2016). However, the statistical and practical importance of such metrics remained unknown; thus Connaboy *et al*. (2016) sought to identify the key kinematic determinants – from those often analysed within sports science support – of performance of UDK in skilled swimmers. A 2D video analysis of seventeen national-level swimmers (eight male and nine female) performing maximum prone UDK was undertaken and a series of backwards elimination ANCOVAs was run. The final model established three covariates to be determinants of the variance in UDK speed: maximal knee angular velocity, maximal ankle angular velocity, and knee range of movement (Connaboy *et al*., 2016). It was not specified, however, whether this was maximal flexion or extension of the knee and ankle. Further, when participant was removed as a fixed factor in the model, only maximal knee angular velocity remained as a significant contributor to UDK speed. The authors concluded the necessity of generating and maintaining a fast knee extension for successful UDK (Connaboy *et al*., 2016). Additionally, the reduction in explained variance when eliminating the fixed factor emphasises the importance of inter-individual differences in technique, and the complex interaction between organismic constraints and performance. This study provides valuable initial insight into the key determinants of UDK; however, there are limitations, including the analysis of only two kick cycles. Additionally, the study was undertaken using national-level swimmers, who only swam in the prone position.

The majority of investigations into the kinematics of UDK have examined prone kicking, and only three have compared prone and supine. Kick frequency and UDK speed have been found to be similar between the two kicking styles (Alves *et al*., 2006; Arellano *et al*., 1999; Scharborough *et al*., 2017), with distance per kick, Strouhal number, and joint amplitudes also not differing based on kick orientation (Alves *et al.*, 2006; Arellano *et al.*, 1999). However, all of these studies were also completed with national or collegiate level athletes, and all comprised a two-dimensional analysis. The majority of UDK studies have used 2D methods and assumed symmetry between the left and right sides of the body. However, from an aerial view of UDK, it can be seen that the medio-lateral positions of the knees, ankles, and feet do not remain constant throughout the kick cycle. There is often internal rotation of the ankle during the knee extension phase, yet the feet can then separate during the knee flexion phase. Consequently, it remains pertinent to establish key kinematic determinants from an elite cohort, in both prone and supine positions, using a three-dimensional approach.

Three-dimensional analysis is considered the most appropriate and accurate method to assess movement in swimming (Arellano *et al.*, 2003; Shimojo *et al.*, 2019). The majority of UDK studies have used 2D methods, yet a scant number have employed 3D analysis, predominantly to explore lower limb kinematics (Yamakawa *et al.*, 2018; Yamakawa *et al.*, 2020(a); Matsuda *et al.*, 2021). When investigating differences in movements at the hip and knee during UDK and butterfly stroke, swimming speed was found to be significantly correlated with peak knee extension angle and peak knee flexion velocity (Yamakawa *et* al., 2018). Interestingly, peak knee extension velocity did not correlate with performance, in contrast with previous studies (Connaboy *et al.*, 2016). It was suggested that a high peak knee flexion velocity helped to ensure a high toe velocity during the upward kick phase (Yamakawa *et* al., 2018). Additionally, peak hip external rotation velocity was correlated with UDK speed (Yamakawa *et al.*, 2018; Matsuda *et al.*, 2021). A key aspect of successful segmental motion is that velocity increases from one segment to the next, and that proximal joint movement therefore contributes to distal segment velocity (Elliott *et al.*, 1995; Miyanishi *et al.*, 1996; Tanabe & Ito, 2007). In combination with the findings of Shimojo *et al.* (2019) that identified a relationship between the external rotation of the lower limbs and the generation of thrust via the production of vortices, it has therefore been suggested that the external rotation velocity of the hip initiates lower limb external rotation (Yamakawa *et al.*, 2020(a); Matsuda *et al.*, 2021).

Previous 3D studies of UDK have notable limitations. Two were completed in a water flume in order to control and manipulate the flow velocity (Yamakawa *et al.*, 2018; Yamakawa *et al.*, 2020(a)). Only two of the studies instructed the participants to swim at maximum effort (Matsuda *et al*., 2021), and none analysed more than three consecutive kick cycles; consequently, an understanding of UDK over the entire underwater phase has not yet been established. Furthermore, all 3D studies were completed prone using male participants. Dolphin kick techniques may differ between men and women, and it is highly likely there are differences between prone and supine kicking due to changes in hydrodynamics. For example, a difference of 117 N in active drag has previously been reported between a male and female swimmer performing UDK (von Loebbecke *et al*., 2009[c]). Finally, no studies have included an analysis of upper limb kinematics, specifically the movement around the shoulders and arms. Consequently, it remains pertinent to investigate a full-body analysis of prone and supine maximal UDK over the full underwater phase, in men and women.

6.1.1 Aims

The aims of this chapter are to:

1. identify which kinematic and temporal parameters correlate with elite UDK performance;
2. establish whether kinematic differences exist in UDK between males and females;
3. establish whether kinematic differences exist between prone and supine UDK.

6.1.2 Hypotheses

It was hypothesised that:

1. Significant associations will exist between kinematic parameters and UDK performance;
2. there would be a significant difference between UDK kinematics of male swimmers and female swimmers;
3. there would be a significant difference between prone UDK and supine UDK kinematics.

6.2. Methods

See Chapter Three - General Methods for equipment details, test protocol, and data processing.

6.2.1 Participant information

Twenty-one swimmers, 11 national (eight male and three female, mean FINA points: 806) and 10 international (six male and one female, mean FINA points: 938) (means ± SDs: 25 ± 2 years; body mass: 72.7 ± 9.9 kg; height: 180.7 ± 9.9 cm) were recruited. Based upon a recent performance classification system, with the aim of standardising results in swimming research, the performance level of the cohort ranged from 1 to 2 (Ruiz-Navarro *et al.*, 2022). Further, of the 10 international athletes, nine were Olympians. Participants were free from injury, and specifically had no incidence of injury over the past year. Furthermore, participants were fully informed of all protocols and potential risks, via written and verbal explanation, and subsequently provided their written consent. Approval from the University Ethics Committee was obtained prior to any procedures.

6.2.2 Definition of variables

A kick cycle was defined as the time between one maximum vertical position of the big toe and its next maximum vertical position. This was verified by visual inspection of the video. The following variables were calculated from the 3D data for each kick cycle within the underwater phase:

- **Highest mean speed over four consecutive kick cycles** – the highest available mean COM speed from four consecutive kick cycles that did not include the first two kick cycles, to eliminate effect of the wall push-off. This was to provide a performance measure that could be standardised across all participants, as not all participants performed the same number of kick cycles.
- **Maximum kick cycle speed ($m \cdot s^{-1}$)** – maximum COM speed within each kick cycle.
- **Minimum kick cycle speed ($m \cdot s^{-1}$) –** minimum COM speed within each kick cycle.
- **Distance per kick (m)** – the horizontal displacement (y-axis) of the COM within each kick cycle.
- **Horizontal COM speed ($m \cdot s^{-1}$) –** kick frequency x distance per kick.
- **Kick frequency (Hz)** – the reciprocal of the time taken to complete one kick cycle.
- **Maximum vertical toe velocity in knee extension/flexion phases ($m \cdot s^{-1}$)**

- **Amplitudes of the hips, knees, ankles, and toes (m)** – the difference between the maximum and minimum vertical displacement (z-axis) values of the respective joint over each kick cycle. Toe amplitude was used as a measure of kick amplitude. Amplitudes were calculated for each side of the body and then averaged to provide one value per joint.
- **Maximum hip, knee, and ankle flexion/extension angle and angular velocity within each kick cycle (°, rad.s^{-1})** – see next section for angle calculation procedure. Angles and angular velocities were calculated for each side of the body and then averaged to provide one value per joint.
- **Shoulder flexion/extension angle –** angle between the arm and the trunk as an indication of deviation away from an aligned position, with 0° indicating perfect alignment between the arm and upper body. See next section for angle calculation procedure.
- **Arm angle of attack (°) –** angle between the shoulder to wrist position vector and the velocity vector of the shoulder. See next section for angle calculation procedure.
- **Knee and foot separation (m)** – maximum and minimum lateral separation (x-axis) of the knees and toes, and time that these occurred within each kick cycle.

6.2.2 Calculation of variables

To enable calculation of joint amplitude, z-coordinate time histories were exported for trochanter, knee, malleolus, and big toe bilaterally. The x-coordinate time histories of the knee and big toe were also exported for the calculation of knee and toe separation.

Hip and knee flexion-extension angle

Hip and knee angles were calculated as the angle defined by three points, specifically; acromion, trochanter, and knee for the hips; and trochanter, knee, and malleolus for the knees. Angular velocities were calculated as the first derivative of the angle data.

Ankle plantarflexion-dorsiflexion angle

Ankle plantarflexion-dorsiflexion angles were determined via the angle between two segments, the shank and the foot. The angle of each segment was computed with respect to an X-Y plane, namely the bottom of the pool. Following this, the foot angle was subtracted from the shank angle. Angular velocities were calculated as the first derivative of the angle data.

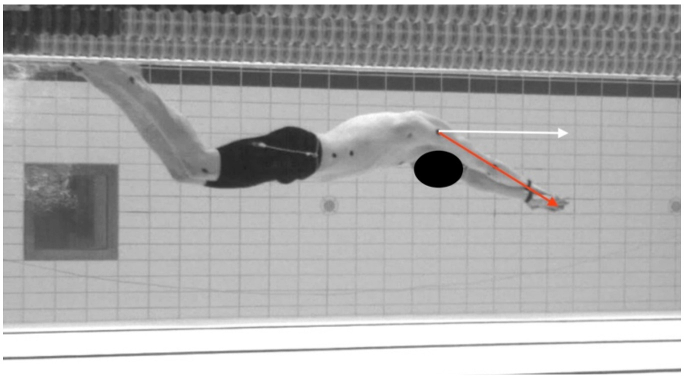
Shoulder flexion/extension angle

The angle of the shoulder to wrist position vector (arm) and the shoulder to hip position vector (trunk) were calculated with respect to the X-Y plane of the bottom of the pool. The trunk angle was then subtracted from the arm angle to give the shoulder flexion/extension angle. For the purposes of this study, 0° indicates perfect alignment of the two vectors; values larger than 0° indicate flexion at the shoulder, whereas values smaller than 0° indicate hyperextension of the shoulder.

Arm angle of attack

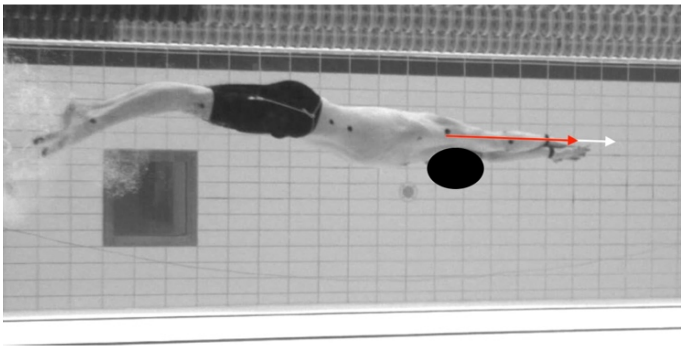
The instantaneous direction of travel of the shoulder was calculated as the resultant of its y and z velocity components [$\mathrm{Tan}^{-1}(v_Z/v_Y)$]. This was then converted to degrees and added to the shoulder-to-wrist position vector to obtain the arm angle of attack.

(a)



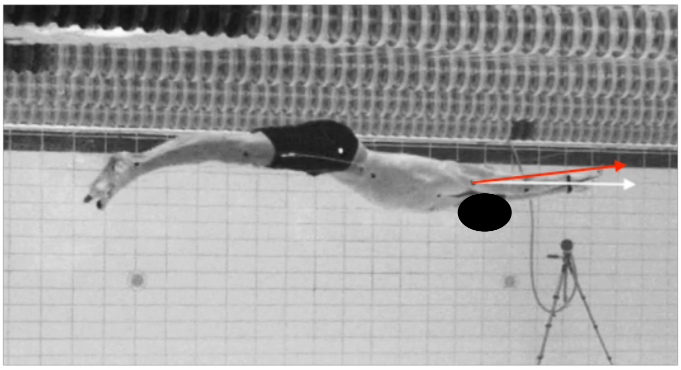
[redacted]

(b)



[redacted]

(c)



[redacted]

Figure 6.1. Examples of (a) positive angle of attack, (b) neutral angle of attack, and (c) negative angle of attack. The white line represents the direction of the velocity of the shoulders, the red line represents the orientation of the arms.

Knee and foot separation

The mediolateral (x-axis) differences between left and right knees and left and right big toes were computed. The maximum and minimum values of these differences within each kick cycle were then determined. The time that these maxima and minima occurred were then expressed as a percentage of the kick cycle.

6.2.3 Statistical analysis

Data were checked for normality via assessment of skewness and kurtosis and the Shapiro-Wilk test. Homogeneity of variance was assessed via Levene's test. To address aim 2 of this study, a correlational analysis was undertaken between all measured variables and the highest mean speed over four consecutive kick cycles, referred to hereafter as UDK performance. For supine trials, the performance variable was non-normally distributed. Consequently, Spearman's Rho correlation procedures were followed for all variables in the supine analysis. For the prone trials, the performance variable was normal, yet three other variables had a non-normal distribution. As such, Pearson's product moment correlations were performed where appropriate, and Spearman's Rho correlations were performed with the remaining three variables. The strength of correlation coefficients was defined as follows: 0 -.19 = very weak, .20 - .39 = weak, .40 - .59 = moderate, .60 - .79 = strong. .80 - 1.00 = very strong (Matsuda *et al.*, 2021).

To address aims 2 and 3 of this study, a comparison between prone and supine UDK performance was undertaken by way of a multivariate analysis of variance (MANOVA). Independent variables were orientation (prone and supine) and sex (males and females); dependent variables were kick frequency, kick amplitude, distance per kick, horizontal COM speed, maximum and minimum kick cycle speeds, maximum toe speeds in upkick and downkick, shoulder flexion/extension angle, arm angle of attack, and knee and toe separation. Where significant differences were found, pairwise comparisons were used to identify where they occurred. Further, effect sizes were estimated using partial eta squared (η2p), and interpreted according to Cohen (1992): .10 - .24 (small), .25 - .39 (medium), ≥ .40 (large).

Although an *a priori* power calculation (effect size = 0.40; α = 0.05, ß = 0.80) suggested a sample size of 32, as a consequence of collecting data on elite athletes within the World Class Programme, it was not possible to obtain trials of the entire cohort swimming prone and supine. Consequently, for the MANOVA, only those athletes who had completed both prone and supine trials were included. This allowed equal sample sizes of n=14 (nine male and five female) for both kicking orientations. Values presented in the tables below, however, include the entire cohort, as included in the correlational analysis.

Due to the participants' underwater phases not being restricted or controlled for depth or distance, in an effort to maintain the highest level of ecological validity, the number of kick cycles analysed varied for each participant. Consequently, to enable an accurate comparison of metrics across participants, and to fully capture the kick-by-kick analysis of each participant's underwater phase, a percentage change metric is also presented to demonstrate how the UDK metrics varied over the trial. This was calculated via a linear regression approach; each variable was plotted and a line of best fit was added. The slope of this line was found and represented the change in variable per kick; this was multiplied by number of kicks to provide the total change over the trial. Finally, the total change was divided by the original value from the first kick cycle and multiplied by 100 to generate the percentage change metric, as per equation 6.1.

Equation 6.1.

$$\%\, change = \left(\frac{total\ change}{original\ value}\right) x\ 100$$

An example of this process can be found in appendix 1 of this thesis.

6.3. Results

The following section is divided into two analyses. First, there is a summary of the correlational analysis to identify which variables correlate with the UDK performance variable, then there is a comparison of UDK when swum prone versus supine. As analyses were undertaken on a kick-by-kick basis, that is, all metrics were calculated for every kick cycle of each participant, values presented represent the group mean of each individual’s trial mean.

6.3.1 Determinants of prone and supine UDK.

Table 6.1 Horizontal COM speeds and displacements, kick frequencies, and maximum and minimum kick cycle speeds for maximal effort prone and supine UDK (mean ± standard deviation). * represents a significant difference between sexes (p <.05). † indicates a significant correlation with UDK performance.

		Highest mean speed over 4 consecutive kick cycles ($m \cdot s^{-1}$)	Horizontal COM speed ($m \cdot s^{-1}$)	Kick frequency (Hz)	Distance per kick (m)	Maximum kick cycle speed ($m \cdot s^{-1}$)	Minimum kick cycle speed ($m \cdot s^{-1}$)
Prone UDK	Male (n=13)	1.74 ± 0.20	1.57 ± 0.16	1.91 ± 0.25	0.83 ± 0.08	1.82 ± 0.19	1.68 ± 0.22
	Female (n=6)	1.58 ± 0.22	1.44 ± 0.17	1.92 ± 0.23	0.76 ± 0.08*	1.65 ± 0.21	1.54 ± 0.19
	All (n=19)	1.69 ± 0.22	1.53 ± 0.17	1.92 ± 0.24†	0.81 ± 0.08	1.76 ± 0.21†	1.63 ± 0.21†
Supine UDK	Male (n=10)	1.78 ± 0.18	1.62 ± 0.17	1.95 ± 0.27	0.83 ± 0.06	1.85 ± 0.17	1.71 ± 0.21
	Female (n=6)	1.63 ± 0.14	1.47 ± 0.12	1.95 ± 0.17	0.76 ± 0.05*	1.68 ± 0.14	1.56 ± 0.10
	All (n=16)	1.73 ± 0.18	1.57 ± 0.17	1.95 ± 0.23†	0.81 ± 0.07	1.79 ± 0.18†	1.65 ± 0.19†

Table 6.2 Maximum toe speeds in knee extension phase and knee flexion phase for maximal effort prone and supine UDK (mean ± standard deviation). ** represents a significant difference between sexes with p <.001; * represents a significant difference between sexes with p <.05.

		Maximum toe speed in knee extension phase ($m \cdot s^{-1}$)	Maximum toe speed in knee flexion phase ($m \cdot s^{-1}$)
Prone UDK	Male (n=13)	3.90 ± 0.24	3.54 ± 0.25
	Female (n=6)	3.52 ± 0.25**	3.22 ± 0.23*
	All (n=19)	3.78 ± 0.30	3.44 ± 0.29
Supine UDK	Male (n=10)	3.96 ± 0.17	3.62 ± 0.33
	Female (n=6)	3.61 ± 0.16**	3.18 ± 0.46*
	All (n=16)	3.83 ± 0.23	3.45 ± 0.43

Table 6.3 Vertical displacement (amplitude) of lower limb joints during maximal effort prone and supine UDK (mean ± SD). * represents a significant difference between sexes with p <.05.

		Hip amplitude (m)	Knee amplitude (m)	Ankle amplitude (m)	Toe amplitude (m)
Prone UDK	Male (n=13)	0.16 ± 0.03	0.29 ± 0.05	0.46 ± 0.07	0.63 ± 0.08
	Female (n=6)	0.13 ± 0.02	0.25 ± 0.03	0.42 ± 0.04	0.57 ± 0.07*
	All (n=19)	0.15 ± 0.03	0.28 ± 0.05	0.45 ± 0.07	0.61 ± 0.08
Supine UDK	Male (n=10)	0.19 ± 0.04	0.30 ± 0.05	0.48 ± 0.07	0.66 ± 0.08
	Female (n=6)	0.14 ± 0.01	0.22 ± 0.02	0.40 ± 0.03	0.56 ± 0.04*
	All (n=16)	0.17 ± 0.04	0.27 ± 0.06	0.45 ± 0.07	0.62 ± 0.08

Prone

A significant, very strong positive correlation was found between UDK performance and both maximum kick cycle speed (*r* = .98, p<.001) and minimum kick cycle speed (r = .99, p< .001) (Table 6.1). Additionally, a significant, strong positive correlation with UDK performance was found for kick frequency (r = .67, p = .002) (Table 6.1); a significant, moderate positive correlation was found for hip extension velocity (r = .53, p = .02) (Table 6.5). A significant, moderate negative correlation was found for knee flexion velocity (r = -.47, p = .04). No other significant correlations were observed.

Supine

A significant, very strong positive correlation was found with UDK performance for both maximum kick cycle speed (r_s = .91, p < .001) and minimum kick cycle speed (r_s = .93, p <.001) (Table 6.1). A significant, strong positive correlation was found for kick frequency (r_s = .68, p = .004) (Table 6.1). Significant, moderate positive correlations with UDK performance were found for hip extension velocity (r = .54, p = .03) and ankle plantar-flexion velocity (r = .53, p = .03) (Table 6.5). Finally, a significant, strong negative correlation was found for hip flexion velocity (r = -.70, p = .003). No other significant correlations were found.

6.3.2 Comparison of male vs female UDK.

A significant main effect with a large effect size was observed for sex (p = .04, η^2p = .96). Pairwise comparisons indicated significant differences between males and females for kick amplitude (p = .01) (Table 6.1), maximum toe speeds in the knee extension phase (p <.001) and knee flexion phase (p = .01) (Table 6.2), distance per kick (p = .01), time of maximum knee separation (p = .03), time of minimum foot separation (p = .00) (Table 6.7). For kick amplitude, distance per kick, and maximum toe speeds, males had higher values than females. The time of maximum knee separation occurred later in the kick cycle for females than males. The time of minimum toe separation occurred later in the kick cycle for males than females (Table 6.7).

6.3.3 Comparison of prone vs supine UDK.

A significant main effect with a large effect size was observed for kicking orientation (p =.03, η^2p = .96). Pairwise comparisons indicated that this reflected significant differences between prone and supine UDK for maximum shoulder flexion/extension angle (p = .01) (Table 6.6); values were higher for supine kicking than for prone. No other significant differences between prone and supine UDK were found.

6.3.4 Change in kick variables during the UDK trial

Table 6.4 Percentage change in kick variable over the entire UDK cycle for kick frequency, distance per kick, horizontal COM speed, and kick amplitude. Values shown are the minimum and maximum percentage change and mean change found for swimmers in the group.

		Kick frequency (%)	Distance per kick (%)	Horizontal COM speed (%)	Kick amplitude (%)
Prone UDK	Male (n=13)	-7 -20 – 9	-9 -30 – 4	-15 -34 – 1	-2 -14 – 7
	Female (n=6)	-6 -21 – 10	-7 -24 – 7	-11 -24 – -7	1 -9 – 29
	All (n=19)	-7 -21 – 10	-9 -30 – 7	-14 -34 – 1	0 -14 – 29
Supine UDK	Male (n=10)	-7 -19 – 6	-6 -15 – 13	-13 -31 – 0	-8 -23 – -2
	Female (n=6)	-7 -18 – 1	-1 -11 – 16	-9 -17 – -2	-7 -13 – 6
	All (n=16)	-9 -19 – 6	-1 -15 – 16	-11 -31 – 0	-8 -23 – 6

Speed

For prone UDK, horizontal COM speed decreased from the start to the end of the trial for all male swimmers apart from two, who experienced a slight increase of 1%. The greatest decline in speed was 34%, corresponding to a 0.68 $m \cdot s^{-1}$ drop over the underwater phase (Table 6.4). The percentage changes for horizontal COM speed were mostly larger than for COM displacement and kick frequency. All female swimmers demonstrated a decline in horizontal COM speed over the underwater phase; the greatest decrease was 24%, a 0.35 $m \cdot s^{-1}$ drop over the phase, and therefore smaller than that of the male swimmers (Table 6.4). For supine UDK, all of the male participants had a decrease in horizontal COM speed except for one, who had no change over the underwater phase. The greatest decline was 31%, corresponding to a 0.52 $m \cdot s^{-1}$ drop over the phase. All female swimmers experienced a decrease in horizontal COM speed over their underwater phase; the largest decline was 17%.

Kick frequency

For prone UDK, kick frequency declined over the underwater phase for almost all the male participants, the greatest decrease being 20%, corresponding to a 0.35 Hz decrease in frequency over the phase (Table 6.4). For one participant there was no change in kick frequency whilst one participant’s kick frequency increased by 9%. The majority of female swimmers had a decline in kick frequency during the trial, with the greatest decrease at 21%, corresponding to a 0.56 Hz drop. One female swimmer increased her kick frequency by 10% over the trial, corresponding to a 0.18 Hz increase. For supine UDK, kick frequency mostly decreased for the male swimmers over the UW phase, the greatest decline being 19% which corresponded to a 0.32 Hz drop in frequency. The largest increase in kick frequency was 6%. All the female participants except one demonstrated a decrease in kick frequency; the largest reduction was 18%, a 0.44 Hz drop. The swimmer that increased frequency did so by just 1%.

Distance per kick

For prone UDK, distance per kick predominantly decreased over the trial for male swimmers, with the greatest decrease being 30%, corresponding to a 0.32 m decrease over the underwater phase (Table 6.4). However, two of the male participants demonstrated a 4% increase in COM displacement over the trial. All female swimmers except one experienced a decline in distance per kick over the underwater phase; the greatest decrease was 24%, a 0.20 m drop (Table 6.4). The one increase in distance per kick was by 7%, a 0.05 m increase. For supine UDK, seven of the 10 male swimmers had a decrease in distance per kick, the greatest of which was 15%, half the percentage decrease of prone kicking. Of the three male swimmers who demonstrated an increase in distance per kick over the phase, the greatest rise was 13%. In contrast, four of the six female swimmers increased their distance per kick, by up to 16% over the UW phase. The greatest decline in distance per kick was 11%, corresponding to a 0.08 m drop.

Joint amplitudes

Amplitudes increased progressively from hip to toe in both prone and supine UDK. Male swimmers produced greater amplitudes than the female swimmers for every joint; additionally, the male swimmers' joint amplitudes for supine UDK were greater than for prone UDK (Table 6.3). When men and women were combined, amplitudes were similar or the same for prone and supine UDK.

For prone kicking, eight of the 13 male swimmers decreased their kick amplitude during their trial; the largest decline was 14% (Table 6.4). Of the five male swimmers whose kick amplitudes increased, the largest rise was 12%. Four of the six female swimmers increased kick amplitude over the UW phase, the greatest being by 29%. The other two female swimmers demonstrated a 9% reduction in kick amplitude over their trial. For supine UDK, kick amplitude decreased for all male swimmers, by up to 23%, a greater extent than for prone kicking. Three of the 10 swimmers experienced only a 2% decline in kick amplitude over the UW phase. Contrastingly, two of the female swimmers increased kick amplitude over the UW phase, by up to 6%, and one experienced no change. The remaining three swimmers demonstrated a decline in kick amplitude, the greatest of which was 13%.

Table 6.5 Lower limb joint angular kinematic variables for maximal effort prone and supine UDK (mean ± standard deviation). * indicates a significant correlation with UDK performance.

		Hip angle (°)		Hip angular velocity (rad•s^{-1})		Knee angle (°)		Knee angular velocity (rad•s^{-1})		Ankle angle (°)		Ankle angular velocity (rad•s^{-1})	
		Max Ext (mean ± SD)	Max Flex (mean ± SD)	Max Ext (mean ± SD)	Max Flex (mean ± SD)	Max Ext (mean ± SD)	Max Flex (mean ± SD)	Max Ext (mean ± SD)	Max Flex (mean ± SD)	Max Plantar Flex (mean ± SD)	Max Dorsi Flex (mean ± SD)	Max Plantar Flex (mean ± SD)	Max Dorsi Flex (mean ± SD)
Prone UDK	Male (n=13)	195.6 ± 6.0	148.6 ± 7.6	5.73 ± 1.37	-6.48 ± 1.35	185.3 ± 7.7	108.6 ± 10.4	9.31 ± 0.79	-8.87 ± 0.82	188.3 ± 9.9	139.8 ± 5.9	6.62 ± 1.76	-6.72 ± 1.31
	Female (n=6)	194.3 ± 7.0	152.9 ± 6.4	5.22 ± 0.65	-5.48 ± 1.30	189.5 ± 6.3	119.4 ± 11.1	8.19 ± 0.93	-7.67 ± 1.21	193.3 ± 11.8	141.8 ± 6.2	6.75 ± 2.73	-6.55 ± 3.79
	All (n=19)	195.2 ± 6.2	149.9 ± 7.4	5.57 ± 1.20*	-6.16 ± 1.38	186.3 ± 7.4	112.0 ± 11.5	8.96 ± 0.97	-8.49 ± 1.09*	189.9 ± 10.5	140.4 ± 6.0	6.66 ± 2.05	-6.67 ± 2.39
Supine UDK	Male (n=10)	197.1 ± 5.0	146.0 ± 7.2	6.36 ± 1.34	-7.00 ± 0.82	183.0 ± 10.4	107.9 ± 10.9	9.04 ± 1.06	-8.63 ± 0.96	188.0 ± 13.1	141.9 ± 4.3	6.76 ± 1.31	-6.16 ± 1.59
	Female (n=6)	195.8 ± 4.7	153.7 ± 5.4	5.58 ± 0.65	-5.69 ± 0.95	190.2 ± 4.7	119.3 ± 6.5	8.25 ± 0.69	-7.94 ± 1.16	196.4 ± 8.6	141.4 ± 6.3	7.77 ± 2.53	-7.32 ± 2.35
	All (n=16)	196.6 ± 4.8	148.9 ± 7.4	6.06 ± 1.18*	-6.51 ± 1.10*	185.7 ± 9.2	112.2 ± 10.9	8.75 ± 0.99	-8.37 ± 1.06	191.2 ± 12.4	141.7 ± 5.0	7.24 ± 1.89*	-6.63 ± 1.87

Table 6.6. Shoulder flexion/extension and arm angle of attack in maximal effort prone and supine UDK (mean ± standard deviation). Presented are the maximum, minimum, and absolute mean values. * represents a significant difference between prone and supine UDK**.**

		Shoulder flexion/extension angle (°)			Arm angle of attack (°)		
		Max	Min	Absolute mean	Max	Min	Absolute mean
Prone UDK	Male (n=13)	23.4 ± 6.1	-5.9 ± 7.4	12.7 ± 3.6	20.0 ± 5.6	5.9 ± 4.7	10.0 ± 2.0
	Female (n=6)	24.2 ± 10.0	1.2 ± 9.0	14.7 ± 6.5	18.9 ± 10.2	4.5 ± 2.7	9.5 ± 5.1
	All (n=19)	23.7 ± 7.3*	-3.7 ± 8.4	13.4 ± 4.6	19.66 ± 7.1	5.5 ± 4.2	9.8 ± 3.2
Supine UDK	Male (n=10)	29.7 ± 4.3	-0.5 ± 6.3	16.1 ± 3.0	23.4 ± 6.0	5.2 ± 2.8	11.5 ± 2.7
	Female (n=6)	29.3 ± 7.6	1.8 ± 4.9	16.6 ± 5.6	16.3 ± 5.4	6.7 ± 2.5	8.8 ± 2.1
	All (n=16)	29.6 ± 5.5*	0.4 ± 5.8	16.3 ± 4.0	20.8 ± 6.6	5.8 ± 2.7	10.5 ± 2.8

Table 6.7. Bilateral knee and foot separation in maximal effort prone and supine UDK (mean ± standard deviation). Values shown are the largest separation (max) and smallest separation (min) of the knees and feet and the time of occurrence expressed as a percentage of the kick cycle time, where 0% is the start of the knee extension phase. * represents a significant difference between sexes.

		Bilateral knee separation				Bilateral foot separation			
		Max (m)	Min (m)	Time Max (%)	Time Min (%)	Max (m)	Min (m)	Time Max (%)	Time Min (%)
Prone UDK	Male (n=13)	0.28 ± 0.03	0.20 ± 0.03	47 ± 12*	38 ± 10	0.13 ± 0.03	0.02 ± 0.02	64 ± 11	43 ± 7
	Female (n=6)	0.25 ± 0.04	0.20 ± 0.04	65 ± 11	35 ± 5	0.13 ± 0.04	0.02 ± 0.02	66 ± 13	34 ± 7*
	All (n=19)	0.27 ± 0.03	0.20 ± 0.03	52 ± 14	37 ± 9	0.13 ± 0.03	0.02 ± 0.02	65 ± 11	40 ± 8
Supine UDK	Male (n=10)	0.27 ± 0.02	0.18 ± 0.03	56 ± 17*	38 ± 6	0.15 ± 0.04	0.02 ± 0.01	58 ± 15	50 ± 8
	Female (n=6)	0.25 ± 0.04	0.20 ± 0.03	64 ± 15	34 ± 4	0.12 ± 0.05	0.03 ± 0.02	62 ± 22	32 ± 13*
	All (n=16)	0.26 ± 0.03	0.19 ± 0.03	59 ± 16	37 ± 6	0.15 ± 0.04	0.02 ± 0.02	62 ± 14	45 ± 10

6.4. Discussion

The aims of this study were to identify which kinematic and temporal variables correlate with elite UDK performance, and establish whether kinematic differences exist in UDK between male and female swimmers, and when performed prone or supine. It was first hypothesised that significant relationships would be found between kinematic parameters and UDK performance. Significant correlations were found between UDK performance and six dependent variables for supine kicking, and five dependent variables for prone kicking. As such, the first hypothesis was accepted. The second hypothesis was that there would be significant differences between UDK kinematics of male and female swimmers. Significant differences between sexes were found in kick amplitude, distance per kick, maximum toe speed in the knee extension and knee flexion phase, and minimum arm angle of attack. Consequently, this hypothesis was also accepted. The third hypothesis was that significant differences would be found between the kinematics of prone and supine UDK. Whilst maximum shoulder flexion/extension angle was significantly larger in supine UDK than in prone UDK, no other significant differences between kicking orientations were found. As such, this hypothesis was rejected.

6.4.1 Associations between UDK performance and kinematic/temporal variables

A significant strong positive correlation was found between UDK performance and kick frequency for prone UDK, in agreement with the existing literature (Arellano *et al.*, 2002; Alves *et al.*, 2006; Connaboy *et al.*, 2009). Maintaining high speed during UDK depends upon the interaction between amplitude and frequency. Kick frequencies were very similar between men and women in the current study, whereas kick amplitudes were 60 cm larger for the males than the females. As the males attained a higher mean speed over four kick cycles, it could be suggested that to improve their UDK, athletes should focus more on increasing amplitude than on frequency. This has also been recommended by Lyttle and Keys (2006) in their work attempting to provide an optimal kick profile. However, this may be a reductionistic approach that neglects to consider the innate physiological and morphological differences between men and women. Indeed, Lyttle and Keys (2006) stated that their conclusions could not be extrapolated to all swimmers.

The present findings may instead reflect the divergent techniques and kicking styles used by men and women. Differences in kicking style may be due to many reasons, including men's larger body size, available muscle mass, and limb length (Wadrzyk *et al.*, 2019). A significant strong positive correlation between the UDK performance and kick frequency was also found for supine UDK; indeed, supine frequencies were slightly higher than those for prone UDK. Given that distance per kick was the same for prone and supine UDK, it is likely that the higher horizontal COM speeds for supine kicking were due to the higher kick frequencies. These findings contrast with previous research that found no significant difference between prone and supine UDK for horizontal velocity or kick rate (Scharborough *et al.*, 2017), or lower swim velocities and frequencies for supine than prone kicking (Alves *et al.*, 2006). However, these studies were completed with collegiate or junior level swimmers, in contrast to the elite and international level of the present cohort. The mean kick frequencies in this study are lower than some previously published values; frequencies for international level swimmers have been reported as 2.14 Hz, with the national group having frequencies of 1.76 Hz (Arellano *et al*., 2002). However, the distance per kick in the present study was higher than those from Arellano *et al*. (2002), 0.81 m compared with 0.76 m and 0.67 m for the international and national groups respectively. Additionally, other studies reporting higher kick frequencies than the present results examined the technique of age-group swimmers. Consequently, discrepancies in findings may be due to differences in sample group.

From this study it would appear that a faster knee flexion velocity results in a faster mean COM speed. A correlation between mean knee flexion velocity and mean COM velocity has previously been found (Higgs *et al*., 2017). It has been previously found that slower swimmers spend comparatively longer in the knee flexion phase than extension phase, whereas faster swimmers spend comparable amounts of time in each phase (Atkison *et al*., 2014). The generation of a large knee flexion velocity will result in a fast knee flexion phase, thereby enabling the athlete to decelerate and change the direction of their feet quickly to commence the next downkick as soon as possible (Atkison *et al*., 2014). Additionally, the increase in knee flexion velocity in faster swimmers may be an attempt to compensate for the lack of comparable joint flexibility present in humans compared to dolphins, and thus a method to emphasise the crucial 'whip-like' action by maximising foot speed in both kick phases (Ungerechts *et al*., 1998; Arellano *et al*., 2002). However, it is surprising that no correlation was observed for knee extension velocity and UDK performance, as this contributes directly to foot speed and has previously been acknowledged to increase effectiveness of the whip-like action (Ungerechts *et al*., 2000; Arellano *et al*., 2002; Connaboy *et al*., 2009). Nevertheless, a fast knee flexion velocity may be key in vortex re-capturing, as it has been purported that vortices separate in areas of high angular acceleration, such as behind the knee during flexion (Hochstein and Blickhan, 2011).

The significant relationship found between UDK performance and plantar-flexion velocity is in agreement with previous literature. It is suggested that, along with the hip and knee, ankle angular velocity is a key component of generating propulsion via the 'whip-like' movement required for skilled UDK (Wang and Liu, 2006; Connaboy *et al*., 2016; Higgs *et al*., 2017). Maximal angular velocity of the ankle has been suggested to be a key determinant of UDK, though only when participant number was included in the model as a measure of between-subject variation. When this factor was removed, only maximum knee angular velocity continued to significantly explain variance in UDK speed (Connaboy *et al*., 2016). The results of this study add to previous investigations by demonstrating a significant correlation during supine UDK, rather than only prone. As such, ensuring high plantar-flexion velocity is recommended for high performance in UDK.

Across both kicking orientations in this study, significant correlations with performance were found for either maximum hip extension velocity, maximum hip flexion velocity, or both. It is interesting that hip extension velocity should correlate with performance in both kicking orientations, as extension is the predominant movement of the hip during the knee flexion phase. Given that the faster swimmers appeared to have a faster hip extension, it could be that these athletes are better able to produce the 'whip-like' movement in both phases of the kick, rather than using the knee flexion phase as a more passive recovery phase. Indeed, the relationship between hip extension and flexion velocity and performance was in agreement with previous literature (Higgs *et al*., 2017; Yamakawa *et al*., 2018). It is suggested that more skilled swimmers have a greater degree of hip extension than do less skilled swimmers, thereby ensuring a fast knee flexion phase (Higgs *et al*., 2017). However, previous studies have not clarified whether the hip velocity involved is under extension or flexion when discussing relationships with performance (Connaboy *et al*., 2016; Higgs *et al*., 2017; Wang and Liu. 2006). As hip extension velocity was found to correlate with performance in both kicking orientations, it would appear that this is a key determining factor in high UDK performance.

6.4.2 Comparison between UDK kinematics of male and female swimmers

In accordance with the second aim of this study, a significant main effect for sex was found. Males had a larger kick amplitude, distance per kick, and maximum toe speed in both the knee extension and knee flexion phases of the kick. This finding was in agreement with previous research that found boys were faster, had greater kick amplitude and distance per kick, than girls (Wadrzyk *et al*., 2019). It was suggested that the difference in distance per kick may be due to the males being biologically predisposed to better performance in anaerobic tasks due to a higher proportion of lean body mass and a concurrently lower percentage body fat (Wadrzyk *et al*., 2019). Additionally, male swimmers likely have longer shanks and thighs and greater propelling surface areas, i.e., bigger feet, than females. Further, differences in body morphology and consequent cross-sectional area may also have an effect, as a moderate positive correlation has been found between the coefficient of drag and the maximal rate of change in shape from the waist to the hip (Papic et al., 2020). Greater curvature around the waist and buttocks could lead to increased hydrodynamic resistance (Papic et al., 2020). In contrast, however, Connaboy *et al*. (2016) observed no significant difference between the sexes for maximum swimming velocity, kick frequency, or distance per kick. Indeed, in other research, the only noted differences between sexes were body lengths (von Loebbecke et al., 2009 [b]), and the way in which the body was positioned relative to a horizontal reference (Arellano *et al*., 2002). The discrepancies in results within these two studies and the present investigation may be due to differences in methodology.

Height, limb length, and available surface area with which to propel the body are, nevertheless, considered key elements to swimming performance, particularly in surface stroking (Kjendlie and Stallman, 2011). However, in the present study, the male and female swimmers with the highest UDK performance were not the tallest athletes of the cohort. Indeed, the fastest female had the smallest body length during prone kicking and the second smallest body length during supine kicking. Additionally, during supine kicking, both swimmers had the smallest kick amplitudes of their group, yet the highest kick frequencies; they also had the highest kick frequencies in prone UDK. The two fastest female kickers in this cohort were the shortest within the group, suggesting that height may not be the decisive factor in good performance in UDK. It has been purported that lean body mass and greater limb segment length ratios are pivotal to 100 m freestyle performance (Nevill *et al*., 2015). For example, a long forearm and shorter upper arm, and a greater foot length alongside a shorter lower leg length, is considered optimal. Within the context of UDK, the greater foot-to-lower-leg ratio is likely the greatest contributor, as a longer foot increases available surface area for propulsion. Whilst these factors were not measured, it could be that limb segment length ratios help to explain the fast UDK speeds achieved by the relatively shorter swimmers. Further research in this area will help to identify if this is the case.

The males in this study had significantly larger maximum toe speeds in both the knee extension and knee flexion phases, in prone and supine UDK, than the females. Both sexes had higher maximum toe speeds in the knee extension phase than in the knee flexion phase, a finding that agrees with previous work (Atkison *et al*., 2014; Gavilan *et al*., 2006). The importance of generating a large toe speed lies in the production of vortices, made possible by the transfer of momentum along the kinematic chain. It has been indicated previously that there is a relationship between the size of vortex produced and the maximum vertical toe velocity (Atkison *et al*., 2014). Skilled swimmers have been shown to produce larger vortices at the end of the knee extension phase than less skilled swimmers, and an additional small vortex at the end of the knee flexion phase (Arellano *et al*., 1999). Consequently, the higher maximum toe speeds of the males may partly explain why they had a higher UDK speed than the females; it could be due to a better proximal-to-distal sequencing by the males compared to the females. However, further research into specific coordination patterns during UDK is required to fully ascertain this; such an examination is conducted in Chapter Seven of this thesis.

Males differed from females in the time of occurrence of maximum knee separation within the kick cycle, with maximum knee separation occurring significantly later in the kick cycle for the females. Though individuals vary in their knee extension and knee flexion phase durations, approximately 0-50% of the kick cycle corresponds to the knee extension phase and the remaining 50-100% to the knee flexion phase. Thus, it can be seen (Table 6.7) that maximum knee separation occurred almost exclusively in the knee flexion phase for both sexes, in both kicking orientations. Additionally, minimum foot separation occurred significantly later for the males than for the females. Similarly to knee separation, on average the feet were widest apart during the knee flexion phase and closest together during the knee extension phase. Bilateral separation of the knees and feet during UDK has not been reported before, nor have any other medio-lateral measures, as bilateral symmetry is often assumed. Evidently, however, this is not the case, as the medio-lateral position of the knees and toes varies throughout the cycle. Anecdotally, from viewing UDK from above, the position of the shanks and feet are different in each kick phase. During the knee extension phase, the toes are often together with the ankles apart, with the opposite positions during the knee flexion phase (Figure A1.2, in appendix 1). This foot position during the knee extension phase possibly creates a bigger surface with which to press the water, thereby potentially acting like a dolphin’s fluke. This may lead to the acceleration of a larger mass of water and therefore increased thrust (Arellano, 1999).

The ankle has previously been found to be adducted and inverted for up to 30% of the kick cycle, after which it abducts and is everted until 60% of kick cycle (Matsuda et al., 2021). These ankle movements correspond with the medio-lateral movement of the toes in the present study. As the ankle inverts during the knee extension phase, the toes will be close together; as the ankle begins to evert and abduct, the toes will separate. Additionally, it has been suggested that the external and internal rotation at the hip during the knee extension phase may affect the direction of the foot (Yamakawa et al., 2018). Indeed, those authors recommended that future research should investigate movements at the foot during UDK. Consequently, the results of this study add to the existing understanding of lower limb kinematics during UDK. As can be seen from Table 6.7, there is a bigger difference between the time of minimum and maximum foot separation for the females than the males. The reason behind this is unclear from these data; however, it may be that the males maintained the inverted position of the ankle for a longer duration than the females. Whilst the degree of internal and external rotation of the ankle was not measured in this study, previous work has demonstrated that a reduction in internal rotation of the ankle results in a reduced UDK speed and kick frequency (Willems *et al*., 2014). Consequently, this may have contributed to the higher UDK speeds from males than females in the present study.

6.4.3 Comparison between prone UDK and supine UDK kinematics

The third aim of this study was to determine if kinematic differences existed between prone and supine UDK. The only significant difference found was that maximum shoulder flexion/extension angle was significantly larger for supine UDK than for prone UDK. Consequently, it can be concluded from the present results that, for this cohort, the kinematics of UDK are similar regardless of kicking orientation.

The maximum shoulder flexion/extension angle denotes the maximum deviation away from 0° of the arms relative to the trunk, with those angles closer to 0° indicating a better alignment of the arms with the upper body. This alignment results in a more streamlined position and reduced drag experienced by the swimmer (Hochstein and

Blickhan, 2011). Conversely, angles greater than 0° indicate a comparative lack of alignment between the arms and upper body. It has been suggested that the upper body's role in UDK is to stabilise the body and sustain a horizontal position (Gavilan *et al*., 2006; Hochstein and Blickhan, 2011). Furthermore, skilled swimmers use their outstretched arms to absorb the excess recoil forces that arise from continuous oscillation of the lower limbs (Connaboy *et al*., 2009; Hochstein and Blickhan, 2014). This mechanism is thought to afford the swimmer a stable platform from which to generate effective undulation with the rest of the body (Connaboy *et al*., 2009). Preferably, the swimmer's arms and trunk would be closely aligned, thereby allowing them to travel through the water in a streamlined position. Having a larger shoulder flexion/extension angle means that, at that given moment, the swimmer is travelling through the water with their arms flexed at the shoulder, thereby presenting a greater frontal area to the oncoming water, and incurring higher drag (Nakashima, 2009). Based upon the maximum and minimum values in this study (Table 6.6), shoulder flexion/extension angles exhibited a range of 27.3° for prone UDK and 28.7° for supine UDK over the kick cycle. Therefore, it can be inferred that the position of the arms relative to the trunk changed throughout the kick cycle. At some point within the kick cycle, the arms were in a position of hyperextension relative to the trunk; at another point, the arms were in a flexed position.

Due to previous simulation research on the upper limbs during UDK (Nakashima, 2009) , it was expected that mean absolute shoulder flexion/extension angle would correlate with UDK performance, and that the fastest swimmers would have angles closer to 0° than the slower swimmers. However, this was not the case, as UDK speed was higher for supine UDK than prone, and yet shoulder flexion/extension angles were greater for supine kicking than prone kicking. An explanation for this discrepancy is unclear; however, it is possible that the increased speed and propulsion of these swimmers when kicking supine is enough to counteract any detrimental resistance incurred from a greater degree of flexion at the shoulder. Though not always significant, UDK speeds, horizontal COM speeds, maximum toe speeds, and maximum and minimum kick cycle speeds were all higher for supine kicking than prone. Additionally, hip extension and flexion velocity and ankle plantar-flexion velocity were also higher for supine kicking than prone. As such, these athletes generally performed better during supine UDK than prone UDK. Such differences in kinematics may have been enough to overcome the potentially greater drag caused by the larger shoulder flexion/extension angle observed in supine trials. Consequently, it may be that in slower swimmers a greater degree of flexion at the shoulder may indeed be detrimental to performance. It may also be a consequence of the smaller sample size than desired, and differing results may have been found with the inclusion of additional swimmers. Further research into the upper limb kinematics of a wider range of skill levels is required to ascertain this.

6.4.4 Change in kick variables over the UDK trial

Horizontal COM speed generally declined during the UDK trials. This effect was observed more in prone UDK than supine UDK, indicating that this cohort was less able to maintain speed in their underwater phase when kicking on their front. In addition, males demonstrated a greater percentage decrease in horizontal COM speed than the females. Indeed, the women in this study were more homogenous than the men in this instance, as the percentage change in all the metrics for the women had a smaller range than those for the men. The larger percentage decrease in horizontal COM speed for the male swimmers is likely a reflection of the concomitant decline in distance per kick, as the percentage changes in kick frequency were similar between sexes. A possible explanation for this may be due to the bigger kick amplitudes demonstrated by the male swimmers; employing and maintaining a larger amplitude requires increased energy to overcome the increase in form drag due to a larger cross-sectional area exposed to the oncoming flow (Chen *et al*., 2022). Subsequently, this excess energy expenditure may be difficult to maintain over the entire underwater phase, leading to a reduction in kick amplitude.

The fastest female kicker within the cohort increased her kick amplitude by 29% over the trial when kicking prone. However, whilst this possibly contributed to the 7% increase in distance per kick over the phase, her kick frequency declined by 21%, resulting in a 14% decrease in horizontal COM speed over her UW phase. It would appear that the rise in kick amplitude was insufficient to counteract the reduction in kick frequency. In contrast, even with an 18% decrease in kicking frequency, the fastest male kicker was able to increase his distance per kick by 11% over the UDK trial when kicking supine, leading to only a 2% drop in horizontal COM speed over his underwater phase. The fastest female kicker demonstrated a similar effect when kicking supine; her distance per kick increased by 16% and kicking amplitude did not change, in spite of an 18% reduction in kicking frequency. It appears that the fastest kickers were able to maintain or increase their distance per kick even with a reduction in kicking frequency or amplitude.

Alterations in amplitude or frequency over the underwater phase may reflect adjustments in technique so as to maintain speed over the trial. When kicking at a higher frequency, the lower limbs will oscillate more quickly than with a lower frequency. Accordingly, in order to achieve a high velocity, force production must be compromised due to the force-velocity relationship, which states that velocity is inversely proportional to muscle load (Siff, 2000). Conversely, a larger kicking amplitude implies larger amplitudes in the joints of the lower limb, as joint amplitudes increase quadratically towards the feet (Hochstein and Blickhan, 2011). As such, the joints will move through a greater range of motion, which has implications both for the length-tension relationship and the joint-torque relationship. The length-tension relationship describes the mechanism by which the greatest amounts of force are produced by a muscle when it is at its approximate resting length due to optimum cross-bridge formation (Lorenz and Campello, 2012). Consequently, changes in joint angle throughout available range of motion will result in a varied number of cross-bridges that can form within the muscle. Additionally, joint angle changes will correspondingly alter the length of the moment arm and, therefore, torque production (Brughelli and Cronin, 2007). As such, it appears that more skilled kickers may be able to adjust aspects of their kinematics so as to maintain speed as much as possible over the underwater phase. The maintenance of distance per kick may be due to an interaction of changes at the joint and muscle level, in contrast to the less skilled kickers who could not maintain their speed over the trial. This demonstrates the importance of examining the underwater phase as a whole rather than only one to three kick cycles as previous research has done.

6.5. Conclusion

This study was the first to conduct a full three-dimensional kinematic analysis of maximum UDK, comparing prone and supine kicking by males and females, on a kick-by-kick basis. Significant relationships were found between UDK performance and six dependent variables for supine UDK, and five dependent variables for prone UDK. Results of this study agree with previous literature that kick frequency is a determining factor in UDK performance. Though no relationship was found between amplitude and the performance variable, amplitudes were 60 cm larger on average for the men than the women. It was thus concluded that the choice of high frequency or high amplitude kicking style should be made based upon the individual athlete's organismic and task constraints, and that no one parameter can be prescribed to all swimmers. The present results also indicated that hip extension velocity, knee flexion velocity, and ankle plantar-flexion velocity are also key factors in UDK performance. Males have significantly greater kick amplitudes, distances per kick, and maximum toe speeds than females, indicating that UDK does differ between males and females. However, with the exception of one upper body variable, no significant differences were found between prone and supine kicking. Consequently, there is no discernible difference between UDK performance when performed prone or supine.

CHAPTER SEVEN

Assessment of Coordination Patterns during Prone and Supine Underwater Dolphin Kick

CHAPTER SEVEN

Assessment of Coordination Patterns during Prone and Supine Underwater Dolphin Kick

7.1 Introduction

The previous chapter in this body of work examined temporal and kinematic parameters of prone and supine underwater dolphin kick (UDK), between males and females. Though it was concluded that hip extension velocity, knee flexion velocity, and ankle plantar-flexion velocity are key factors in performance, there were some findings that required a more detailed investigation into the coordination patterns underpinning UDK performance. As such, this chapter addresses those remaining questions, thereby continuing the thematic narrative throughout the thesis.

Despite general coaching and practitioner consensus that successful UDK is reliant upon precise sequential coordination of segments, there are few studies examining the nature of this coordination amongst swimmers. In addition, there appears to be no consensus on the most appropriate method to describe coordinative patterns within UDK. Cross-correlations have been used in an attempt to identify and describe the predominant motor coordination during this skill (Elipot et al., 2016). These researchers found no significant correlations between the swimmers' centre of mass velocity and any joint angles or vertical accelerations of joints. However, some significant cross-correlation functions were found between kinematic variables. It was suggested that higher-skilled swimmers manipulated the coordination of their lower limbs to ensure kicking amplitude did not become so large as to cause a detrimental increase in form drag (Elipot *et al.*, 2016). A collaborative action from the hip and ankle was purported to increase the angles of attack of the trunk and thigh; the potential effects of this on drag were thought to be regulated by movement from the knee, thereby controlling amplitude. However, it was not stated what these joint actions were, and it was concluded that cross-correlations may not be the most appropriate method by which to fully understand the complex action of multiple joints in achieving high velocities in UDK (Elipot et al., 2016).

As an alternative to cross-correlations, continuous relative phase (CRP) has been used to quantify coordination during movement tasks. Continuous relative phase is a spatio-temporal measure that describes the coupling relationship between two segments or limbs throughout a movement cycle (Lamb and Bartlett, 2017; Wheat and Glazier, 2006). Its use is particularly appropriate when investigating coordination within a dynamical systems framework. This framework models human behaviour as a complex system, a structure with many interacting components, each with the possibility of affecting each other (Davids *et al*., 2008). Within the context of the human movement system, these components are referred to as degrees of freedom. For example, there are three degrees of freedom at the shoulder joint, flexion/extension, internal/external rotation, and abduction/adduction (Gielen *et al*., 1998). The final position of the arm is determined not only by the rotations at each joint, but also the order in which they rotate. However, often there are more degrees of freedom available than are required for a given task, a phenomenon known as motor redundancy (Bernstein, 1967). In the context of skilled performance, the large and potentially redundant number of degrees of freedom available within the system are reduced by means of generating coordinative strategies or structures (Hamill *et al*., 1999; Stergiou *et al*., 2001; Wheat and Glazier, 2006).

Movement strategies arise from and are manipulated by three different types of constraints applied to the system: organismic, environmental, and task-related (Davids *et al*., 2008; Newell, 1986). A constraint is a variable that can inhibit or enable movement, by either restricting movement to a specific pattern, or facilitating an individual to explore possible movement solutions (Robins, 2013). For example, an organismic constraint may be a person’s height, and a crucial environmental constraint within swimming is the water and the consequential fluid forces acting upon the swimmer. Importantly, however, it is the interaction of these constraints that leads to behaviour; the continuous interaction of constraints on the system result in self-organisation of that system. Self-organisation refers to the way in which functional movement patterns emerge as a result of internal processes, rather than from external prescription (Yates, 1983). As such, stable patterns of movement will develop in response to continuous adaptation to the constraints interacting with a system.

In contrast to traditional approaches of movement behaviour and motor control, in which variability is often viewed solely as disadvantageous, within dynamical systems theory (DST) the presence of large amounts of movement variability can indicate a change in coordination mode (Hamill *et al*., 1999). In addition, it can indicate if a movement pattern is stable; these stable patterns arise when the system is functioning in its preferred state, without perturbation, and are otherwise known as attractors (Davids *et al.*, 2008; Glazier and Davids, 2009). In order to assess the state of these stable movement patterns, and how they change over time, it is necessary to identify variables that encompass all aspects of the system involved. In other words, a dependent variable that describes the behaviour of the joints or segments involved in a given movement. Analysis of this variable over time should therefore enable the identification of a coordinated movement pattern (Stergiou *et al.*, 2001). The CRP between limbs and between segments within limbs has been previously considered an appropriate variable for assessment of inter- and intra-limb coordination (Hamill *et al.*, 1999; Kelso, 1984; Stergiou *et al.*, 2001).

At any given point throughout the movement cycle, the CRP between two segments or limbs is defined as the difference between their respective phase angles (Wheat and Glazier, 2006), a difference in phase between two signals expressed as an angle. By subtracting one segment's phase angle from the other, it can be determined whether the coordination is 'in-phase' or 'anti-phase'. In-phase coordination denotes that the two segments or limbs are performing the same action, e.g., both are flexing or extending (Lamb and Bartlett, 2017; Stergiou *et al.*, 2001). In contrast, anti-phase describes the situation when segments are performing opposing actions, e.g., one is flexing whilst the other is extending. This concept was initially described by Kelso (1981,1984) via a series of experiments involving finger oscillations. Beginning at a low frequency of movement, participants were instructed to move their index fingers in an anti-phase mode, that is, one finger pointing towards the middle of the body and one pointing away (i.e., both pointing to the right and then both pointing to the left). As movement frequency increased by way of a metronome, all participants unconsciously switched to an in-phase mode, in which both fingers pointed towards the midline of the body (i.e., one pointing right and one pointing left, towards each other). It was suggested that this in-phase pattern was more stable, leading to its emergence as a result of change in frequency, and is an example of self-organisation.

In-phase and anti-phase patterns of coordination clearly take place in oscillation of small joints such as the fingers. However, as human movement is often complex, coordination is rarely perfectly in-phase or anti-phase. Anywhere in between these two extremes is considered to be relatively more in-phase or more out-of-phase (van

Emmerik *et al*., 2014). As CRP is a continuous measure, these nuances in coordination can be identified and described. Angle-angle diagrams can also describe the movement of one segment or joint with respect to another. The plotting of one joint's angular displacement data against that of another can provide a valuable qualitative depiction of relative motion between the two joints. This is often a useful first step in describing and understanding inter-joint coordinative patterns. Following this, CRP can then provide a detailed quantitative analysis of those patterns (Burgess-Limerick *et al*., 1993). With CRP, both spatial and temporal information are incorporated into one measure, enabling the interpretation of motor patterns, and how they change, over a specified time period. Furthermore, CRP includes angular velocity data as well as angular displacement, providing a higher-order analysis of coordination than angle-angle diagrams (Stergiou *et al*., 2001;Van Emmerick *et al*., 2014).

The predominant focus of previous work using CRP has been either hand movement or gait research. However, some investigations into aquatic motion using CRP have been undertaken, including an examination of the variability in inter-limb coordination during maximum effort 200 m freestyle (Figueiredo *et al*., 2012). Though differences were demonstrated in temporal variables, with adjustments made to account for fatigue, the anti-phase movement pattern of the upper limbs did not change over the course of the 200 m effort. This was suggested to be due to the uniformity of skill level across the cohort (Figueiredo *et al*., 2012). Interestingly, however, two distinct clusters of coordination profiles were observed; one group of swimmers demonstrated lower CRP variability and less time spent in the glide phase than the other. This was suggested to be due to either the organismic constraint of the swimmer's individual technique, or task-specific constraint i.e., the swimmer's main event race distance (Figueiredo *et al*., 2012). Though this study utilised CRP to examine inter-limb coordination within swimming on the surface of the water, UDK is characterised by submerged intra-limb coordination, due to the lower limbs working collectively to propel the swimmer through the water. Connaboy *et al*. (2007[b]) analysed the phase relationships between the shoulder, hip, knee, and ankle during UDK in skilled and unskilled swimmers via Fourier analysis, to assess if propulsive waveforms could be detected. Though no differences were found in mean phase angle between groups, variability (determined by standard deviation) did differ for kick frequency and mean phase angle for all vertical joint oscillations (Connaboy *et al.*, 2007[b]), with skilled swimmers demonstrating less variability.

Continuous relative phase was used in an investigation into the intersegmental coordination of the pelvis-trunk movement during the butterfly stroke and UDK (Nikodelis *et al.*, 2013). It was demonstrated that coordination modes differed between butterfly and dolphin kick, with the former comprising a more in-phase mode and the latter more out-of-phase (Nikodelis *et al.*, 2013). The authors stated that there was no difference between the pelvis-trunk coordination between prone and supine kick for this swimmer; however, no statistical analysis was completed, likely as a result of the sample size of one swimmer. It was suggested that the out-of-phase movement during UDK was a mechanism with which the upper trunk maintains stability of the body, in agreement with previous literature (Connaboy *et* al., 2009; Nakashima, 2009). Although this study utilised CRP to assess coordination, only one swimmer was included, and the focus was on the movement of the trunk and pelvis. Whilst these segments are important in creating the wave required for successful UDK, it has been previously identified that the majority of the thrust in UDK comes from the feet, with the upper body not directly contributing to propulsion (Sugimoto *et al.*, 2008). Consequently, it remains pertinent to investigate the coordination at the joints of the lower limb within a cohort of elite swimmers.

An element of UDK that is considered to be essential for optimum performance is a sequential movement of body segments to enable a caudal transfer of momentum (Arellano *et al.*, 2002; Higgs *et al.*, 2017). Functionally, this is to ensure each segment’s velocity is faster than the previous one, so that ultimately the foot has the highest velocity. To ensure this high end-point speed, a proximal-to-distal sequencing of movements is required, in which the segments closer to the trunk rotate first, followed by each successive segment, and concluding with rotation of the most distal segment (Lees, 2008). In this way, the distance between the origin of the rotational movement and the end-point is increased, and the limb or limbs are close to full extension. As the build-up in speed is cumulative from each segment to the next, the most distal segment will have the highest velocity (Lees, 2008). This mechanism is also known as the ‘summation of speed principle’ (Bunn, 1972), yet within the context of UDK, it is often referred to as the ‘body wave’ (Connaboy *et al.*, 2009; Gavilan *et al.*, 2006; Higgs *et al.*, 2017; Hochstein and Blickhan, 2014), describing the propulsive waveform that travels along the body due to temporally sequenced oscillations, and has been identified as an important factor for performance (Connaboy *et al*., 2009). Propulsive waveforms have been reported in a study comparing skilled and unskilled kickers, using mean phase angle data (Connaboy *et al*., 2007[b]). However, as the velocity of each segment is a key contributing factor to propulsion, it would be interesting to explore the velocities of the segments implicated in UDK. The time at which each segment reaches its maximum velocity may indicate the presence or absence of proximal-to-distal sequencing of momentum transfer along the kinematic chain.

The limited number of studies that have investigated coordination within UDK have either been completed prone or have not specified kicking orientation. The one study that did compare prone and supine kicking was only completed with one participant, rendering inferential statistics impossible. Consequently, it is not known whether the coordination strategies adopted during supine kicking are the same as during prone kicking. Additionally, there is little understanding of how movement patterns change throughout the kick cycle and in the different phases. As previously mentioned, most kickers are able to successfully perform the knee extension phase, yet skilled kickers are able to generate propulsion from both phases of the kick (Atkison *et al*., 2014). This discrepancy between skill levels may be explained by a difference in coordination pattern, with some kickers demonstrating effective coordination in the knee extension phase only.

As established, CRP can be used to quantify coordinative patterns in cyclical movements, and the assessment of variability can help identify the presence or absence of stable states of coordination. Additionally, it has been demonstrated that this method of quantifying coordination can be used in the analysis of swimming and UDK. However, there remain a few questions to be addressed in the assessment of UDK coordination, particularly of the lower limbs. First, whilst coordination has been compared between ‘skilled’ and ‘unskilled’ kickers, the average velocities reported for even the skilled kickers (1.34 $m.s^{-1}$) are lower than those reported in Chapter Six of this thesis. As such, it would seem that the previous sample, though skilled, may not be classified as ‘elite’, and it remains pertinent to examine coordination patterns of this level of swimmer performing UDK. In addition, there have been no investigations into whether differences exist between the coordination of men and women performing

UDK. Considering the variation in organismic constraints between men and women, for example, height and limb length, differences in coordinative strategies may well be present between sexes. Finally, it remains unclear if the same strategy and sequencing within the lower limbs is used for prone and supine UDK, or if each orientation requires a different approach. Given that these differences have not been examined previously, such a comparison would present novel findings and add considerably to the current body of knowledge on coordination patterns in UDK. This could have implications for coaching practices in improving athletes' technique, both at the elite and age-group level.

7.1.1 Aims

The aims of this chapter are to:

1. determine if movement patterns in maximum effort UDK demonstrate a temporal sequence in both phases of the kick cycle;
2. determine whether differences exist in coordination between prone and supine UDK;
3. determine whether differences exist in coordination between males and females;

7.1.2 Hypotheses

It was hypothesised that:

1. a temporally sequential movement pattern would be observed for the knee extension phase of the kick cycle, but not for the knee flexion phase;
2. differences would exist in CRP between supine and prone UDK;
3. differences would exist in CRP between UDK by males and females;

7.2.0 Methods

See Chapter Three - General Methods for equipment details, test protocol, and data processing.

7.2.1 Participant information

Fourteen swimmers, eight national (five male and three female, mean FINA points: 786) and six international (four male and two female, mean FINA points: 932) level, (means ± SDs: 25 ± 2 years; body mass: 72.7 ± 9.9 kg; height: 180.7 ± 9.9 cm) were recruited. Based upon a recent performance classification system, with the aim of standardising results in swimming research, the performance level of the cohort ranged from 1 to 3 (Ruiz-Navarro *et al.*, 2022). Further, of the 10 international athletes, nine were Olympians. Participants were free from injury, and specifically had no incidence of injury over the past year. Furthermore, participants were fully informed of all protocols and potential risks, via written and verbal explanation, and subsequently provided their written consent. Approval from the University Ethics Committee was obtained prior to any procedures.

7.2.2 Data processing

A kick cycle was defined as the time between one maximum vertical position of the big toe and its next maximum vertical position. This was verified by visual inspection of the video. Processing of the data was undertaken in three parts: a temporal analysis, generation of angle-angle plots, and calculation of CRP.

7.2.2.1 Temporal analysis

A temporal analysis was conducted to identify if movement patterns were sequential. The vertical velocity time-histories of the centre of gravity of four segments over three consecutive kick cycles were isolated from each trial (Figure 7.1). These segments were the trunk, thigh, shank, and foot, as the main drivers of movement in UDK. The vertical velocity time-histories were used as movement in UDK is predominantly within the vertical direction. It was posited that assessing the vertical velocity of the centre of gravity of the segments would indicate if velocity increased down the chain as per the summation of speed principle. The maximum and minimum values within each kick cycle were then extracted; these corresponded to the peak upward and downward velocity occurring in the two respective phases of the kick cycle. The times that these peaks occurred were then expressed as a percentage of kick cycle time, denoted as each segment Vz cycle time %.

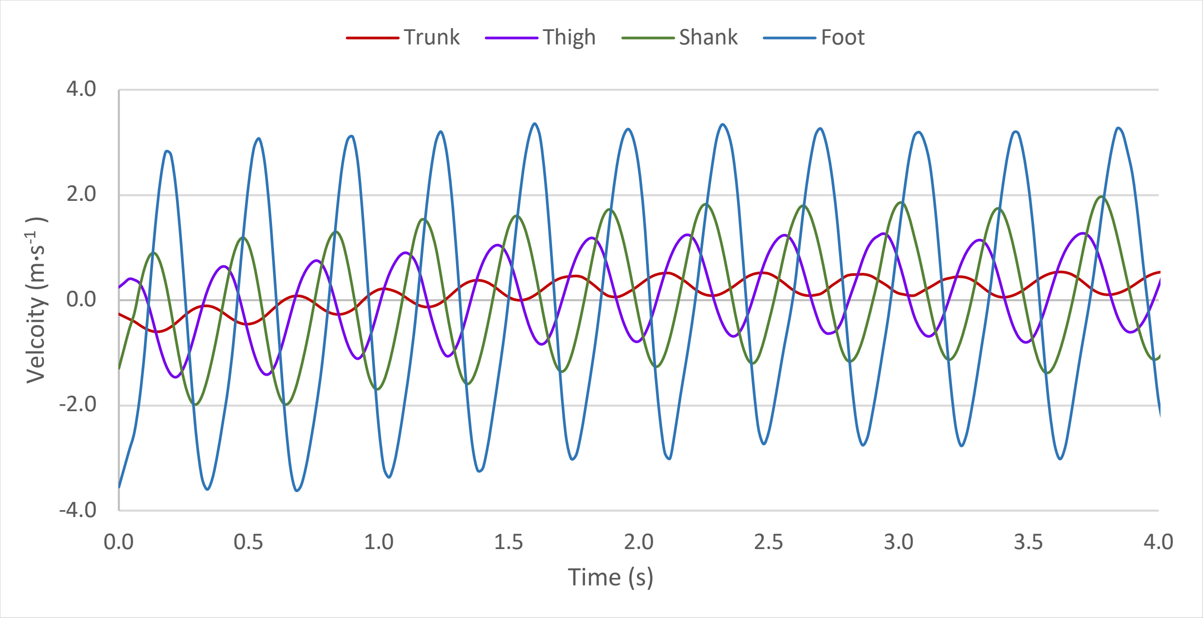


Figure 7.1. Example plot of one participant's vertical velocity time-history of the trunk, thigh, shank, and foot.

7.2.2.2 Angle-angle plots

Angle data were calculated for the hips and knees as per Chapter Six of thesis. These were then plotted against each other to demonstrate graphically when the hips and knees were flexing and extending throughout the kick cycle.

7.2.2.3 Continuous relative phase

To provide a quantitative analysis of coordination patterns, CRP was calculated for the couplings between hip and knee (hip/knee) and knee and ankle (knee/ankle). Phase plane portraits were created for each joint, comprising the joint angle along the *x* axis and angular velocity along the *y* axis. Normalisation of the angle position and angular velocity data was required, to adjust for the frequency and amplitude differences between them and enable analysis of intra-limb coordination (Hamill *et* al., 2000; van Emmerick *et al*., 2014; Wheat and Glazier, 2006). The angle position data were normalised via equation 7.1:

Equation 7.1

$$\theta_i = \frac{2 \times [\theta_i - \min(\theta_i)]}{\max(\theta_i) - \max(\theta_i)}$$

where θ is the segment angle at each time point.

The angular velocity data were normalised via equation 7.2:

Equation 7.2

$$\omega'_i = \frac{\omega_i}{\max[max(\omega_i), max(-\omega_i)]}$$

Normalisation procedures were conducted using the maximum value over the three kick cycles, to better retain the spatial properties between cycles (Hamill *et al*., 2000). Phase angles were then calculated via equation (7.3):

Equation 7.3

$$\varphi = \tan^{-1}\frac{\omega(t)}{\theta(t)}$$

The phase angle is denoted by the angle between the right horizontal and the line drawn to each data point within the phase plane portrait (Figure 7.2).

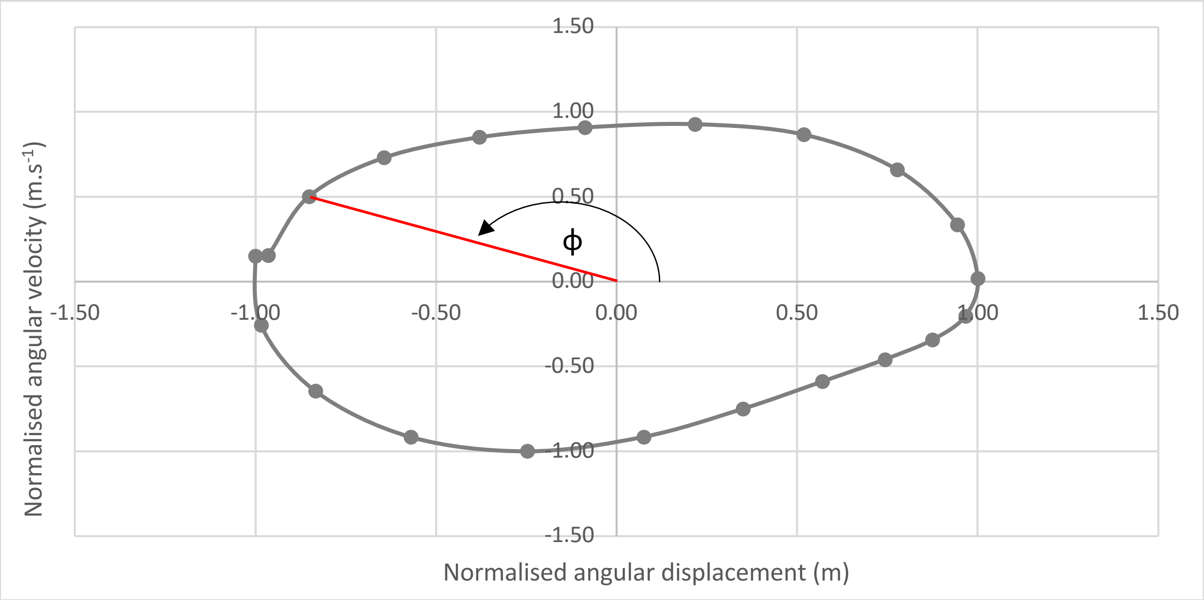


Figure 7.2. Phase plane portrait demonstrating how the phase angle is calculated. Angular position data is on the *x* axis with angular velocity on the *y* axis. The phase angle is calculated as the angle between the right horizontal and the line to each data point.

Phase angles were then restricted to the range 0-180° in order to avoid discontinuities in the data between quadrants two and three, and therefore the resulting CRP data (van Emmerick *et al*., 2014, Wheat *et al*., 2003). The distal segment was then subtracted from the proximal segment, to provide CRP values over the three consecutive kick cycles.

$$\mathrm{CRP}_{(t)} = \mathrm{CRP}_{\mathrm{proximal}} - \mathrm{CRP}_{\mathrm{distal}}$$

To enable statistical analysis, for every participant each of the three kick cycles was interpolated to the longest kick cycle, whilst maintaining the start and end points of the cycle (Hamill et al., 1999; Van Emmerik and Wagenaar 1996[b]). The mean of the three kick cycles was then used to calculate participant ensemble CRP curves for both hip/knee and knee/ankle coupling. From these ensemble curves, the CRP values at the start (CRPstart) and end points (CRPend) were extracted, alongside the value at the transition point (CRPtransition) between phases within the kick (i.e., between knee extension phase and knee flexion phase). Additionally, the mean CRP over the knee extension (CRPext) and knee flexion (CRPflex) was determined. The between-cycle standard deviation at each point across the three kick cycles was calculated and represented the variability in relative phase (Hamill et al., 1999; Van Emmerik and Wagenaar 1996[b]; Wheat and Glazier, 2006). Following this, the mean standard deviation over each kick phase was determined (SDext and SDflex).

7.2.3 Statistical analysis.

A series of mixed ANOVAs was performed to establish if CRP differed between prone and supine kicking. An *a priori* power calculation (effect size = 0.40; α = 0.05, ß = 0.80) denoted the minimum number of participants required to observe a statistical difference was 12. Data were first checked for normality and homogeneity of variance. For some of the dependent variables, the assumption of homogeneity of variance was violated, and data had to be logarithmically transformed prior to the analysis (Field, 2009). The ANOVAs were performed for each variable outlined above, for both hip/knee and knee/ankle couplings; kicking orientation (prone and supine) served as the within-subject factor, whilst sex was the between-group factor (males vs females). Further, effect sizes were estimated using partial eta squared (η^2_p), and interpreted according to Cohen (1992): .10- .24 (small), .25-.39 (medium), ≥.40 (large). Data were analysed with IBM SPSS Statistics for Windows (Version 27.0, Armonk, NY: IBM Corp.).

7.3.0 Results

7.3.1 Temporal analysis

Table 7.1. Times that the trunk, thigh, shank, and foot mass centres reached maximum vertical velocity in the knee flexion phase, expressed as a percentage of kick cycle. The range of times for each group's value is reported in parentheses under the value.

		Trunk Vz Cycle time (%)	Thigh Vz Cycle time (%)	Shank Vz Cycle time (%)	Foot Vz Cycle time (%)
Prone UDK	Males (n=9)	21 (12-28)	38 (31-42)	58 (51-66)	70 (64-77)
	Females (n=5)	38 (17-63)	53 (32-87)	57 (35-78)	55 (19-76)
	All (n=14)	26 (12-63)	43 (31-87)	58 (35-78)	65 (19-77)
Supine UDK	Males (n=9)	19 (13-29)	36 (30-41)	57 (53-60)	70 (65-72)
	Females (n=5)	13 (5-14)	35 (31-38)	57 (50-59)	68 (64-71)
	All (n=14)	17 (5-29)	36 (30-48)	57 (50-60)	69 (64-72)

Table 7.2. Times that the trunk, thigh, shank, and foot mass centres reached maximum vertical velocity in the knee extension phase, expressed as a percentage of kick cycle. The range of times for each group's value is reported in parentheses under the value.

		Trunk Vz Cycle time (%)	Thigh Vz Cycle time (%)	Shank Vz Cycle time (%)	Foot Vz Cycle time (%)
Prone UDK	Males (n=9)	69 (62-75)	86 (3-95)	10 (6-15)	27 (24-30)
	Females (n=5)	53 (14-68)	70 (43-86)	18 (7-59)	34 (24-74)
	All (n=14)	64 (14-75)	81 (3-95)	13 (6-59)	29 (24-74)
Supine UDK	Males (n=9)	69 (58-76)	90 (75-100)	10 (8-15)	26 (21-31)
	Females (n=5)	61 (54-64)	88 (83-94)	35 (12-76)	26 (24-28)
	All (n=14)	66 (54-76)	89 (75-100)	19 (8-76)	26 (21-31)

Prone Kicking: For the knee flexion phase, a sequential movement pattern was observed for the males. The trunk, thigh, shank, and foot segments reached maximum vertical velocity in a proximal-to-distal sequence at 21%, 38%, 58%, and 70% of kick cycle respectively (Table 7.1) Conversely, the females' data did not demonstrate a sequential pattern; their segments reached maximum vertical velocity at 38%, 53%, 57%, and 55% (Table 7.1) respectively, meaning the foot reached maximum velocity before the shank. For the knee extension phase, neither males nor females demonstrated a sequential movement pattern. All participants' shanks reached maximum vertical velocity first (10% and 18% of kick cycle for males and females respectively), followed by the foot, then the trunk, and finally the thigh (Table 7.2).

Supine Kicking: For the knee flexion phase, a sequential movement pattern was observed for both males and females (Table 7.1). For the knee extension phase, neither males nor females demonstrated a sequential movement pattern. With respect to the male data, the shank reached maximum vertical velocity first; however, the foot reached maximum vertical velocity first for the females. For both sexes, the thigh was last to reach maximum vertical velocity (Table 7.2).

7.3.2 Angle-angle diagrams

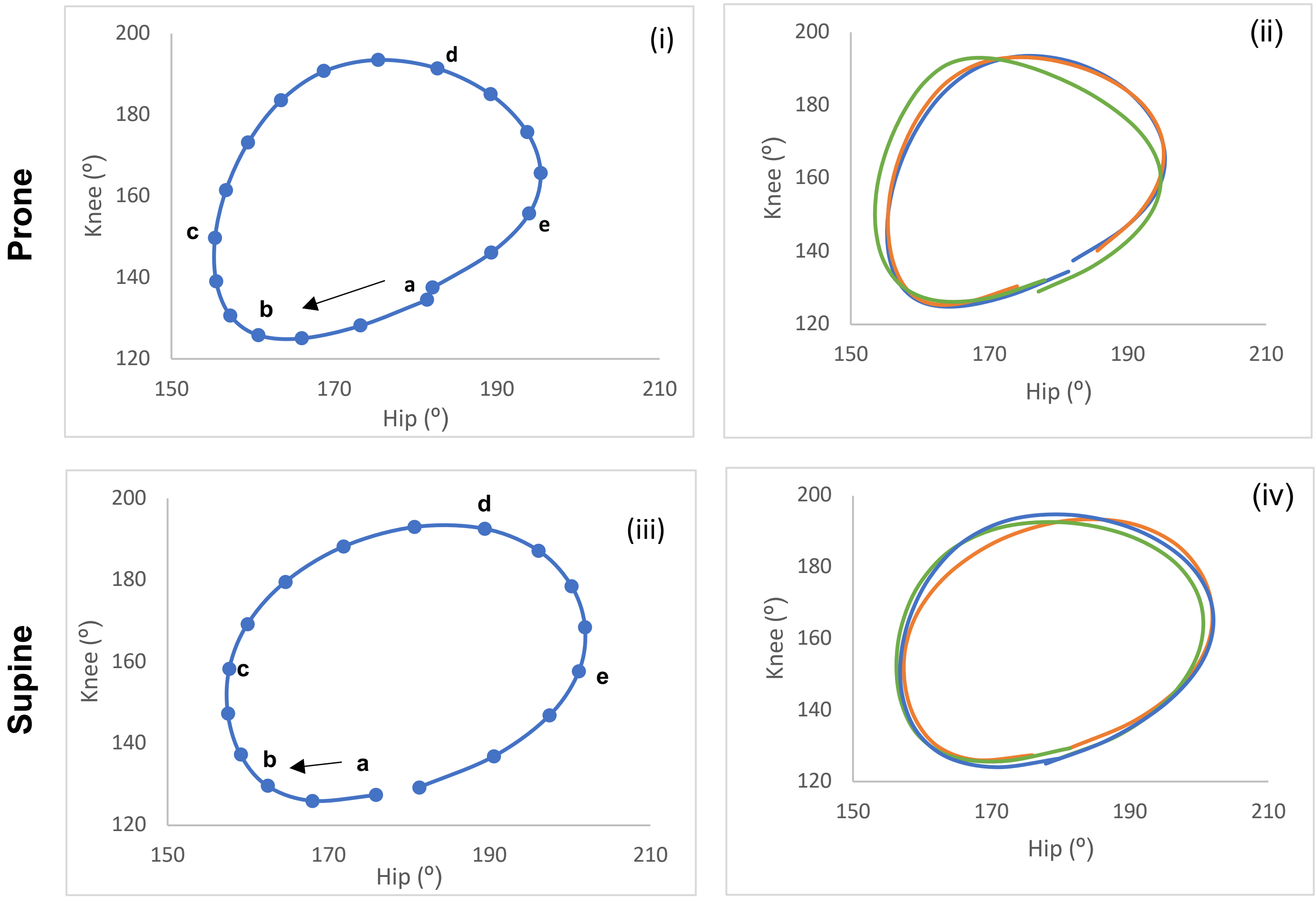


Figure 7.3. Hip and knee angle-angle plot for the fastest male kicker for (i) one prone kick cycle, (ii) three consecutive prone kick cycles, (iii) one supine kick cycle, and (iv) three consecutive supine kick cycles. Blue line represents kick cycle one, orange line represents kick cycle two, green line represents kick cycle three.

Reading Figure 7.3 (i) and (iii) clockwise, with *a* representing the start of the kick cycle, between *a* and *b* both the hip and knee are briefly flexing; between *b* and *c* the hip continues to flex whilst the knee begins to extend. After *c*, both the hip and knee are extending until *d*, at which point the knee begins to flex. The hip continues to extend until *e*, after which both hip and knee are flexing. The shapes of the plot differ slightly between prone and supine kicking (Figure 7.3 (i) and (iii) respectively). For prone kicking, the line between *c* and *d* is more vertical than that for supine kicking. This indicates that the knee is extending faster relatively than the hip is extending.

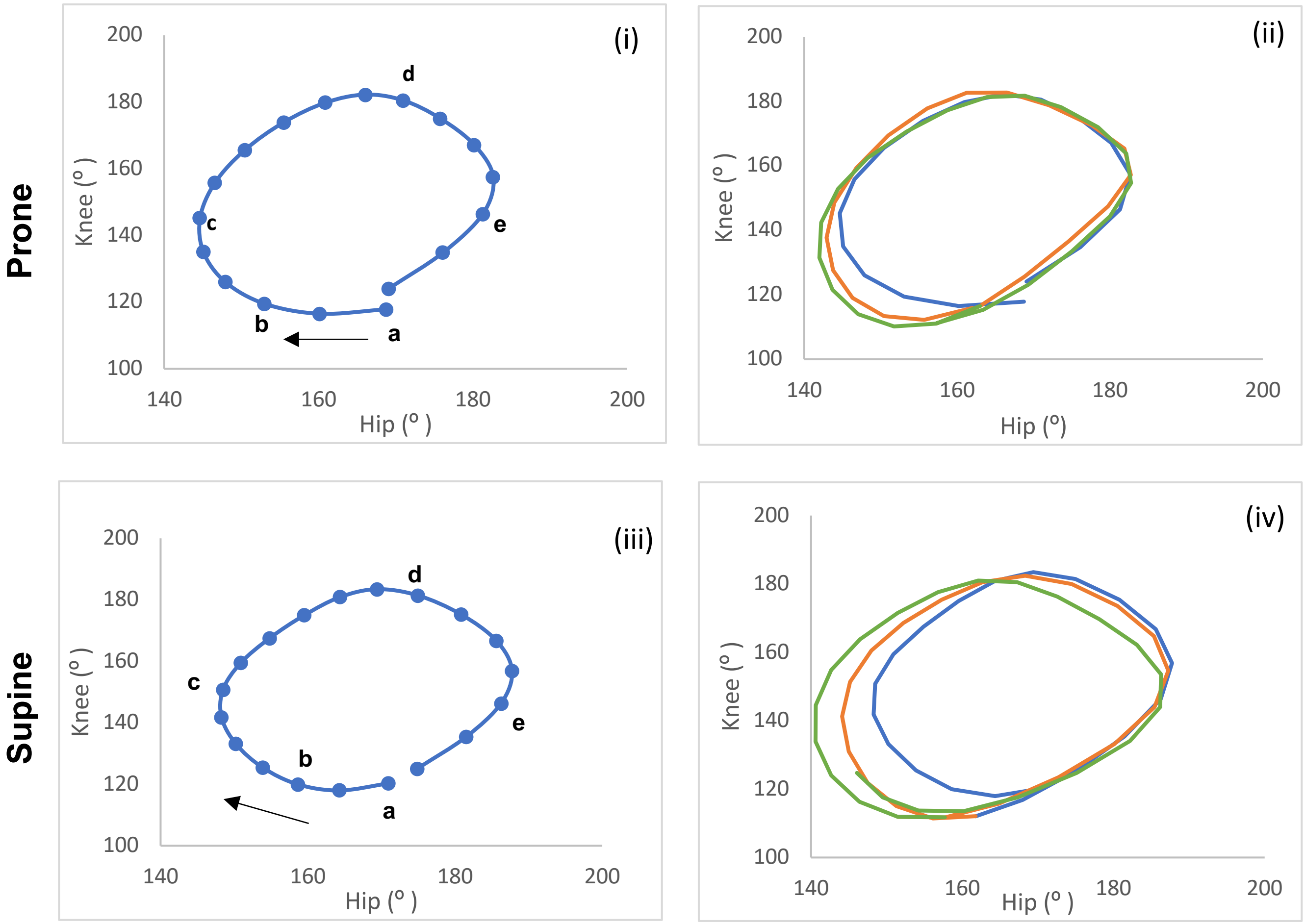


Figure 7.4. Hip and knee angle-angle plot for the fastest female kicker for (i) one prone kick cycle, (ii) three consecutive prone kick cycles, (iii) one supine kick cycle, and (iv) three consecutive supine kick cycles. Blue line represents kick cycle one, orange line represents kick cycle two, green line represents kick cycle three.

Reading Figure 7.4 (i) and (iii) clockwise, with *a* representing the start of the kick cycle, between *a* and *b* both the hip and knee are flexing. At point *b* the knee begins to extend; the hip continues to flex until *c*, after which both the hip and knee extend. Between *d* and *e*, the knee is flexing whilst the hip continues to extend; finally, at *e*, the hip also begins to flex. For this swimmer, the plots for prone and supine are very similar. However, looking at Figure 7.4 (ii) and (iv), the three consecutive kick cycles demonstrate some variation. This is most prominent for supine UDK (Figure 7.3 (iv)), in which each circle is larger than the previous one, predominantly in the lower left quadrant of the plot. The larger circle indicates a larger amount of hip and knee flexion before both joints switch to extension, than the smaller circle. The hip and knee went through a larger range of motion for flexion for kick cycles 2 and 3 than cycle 1.

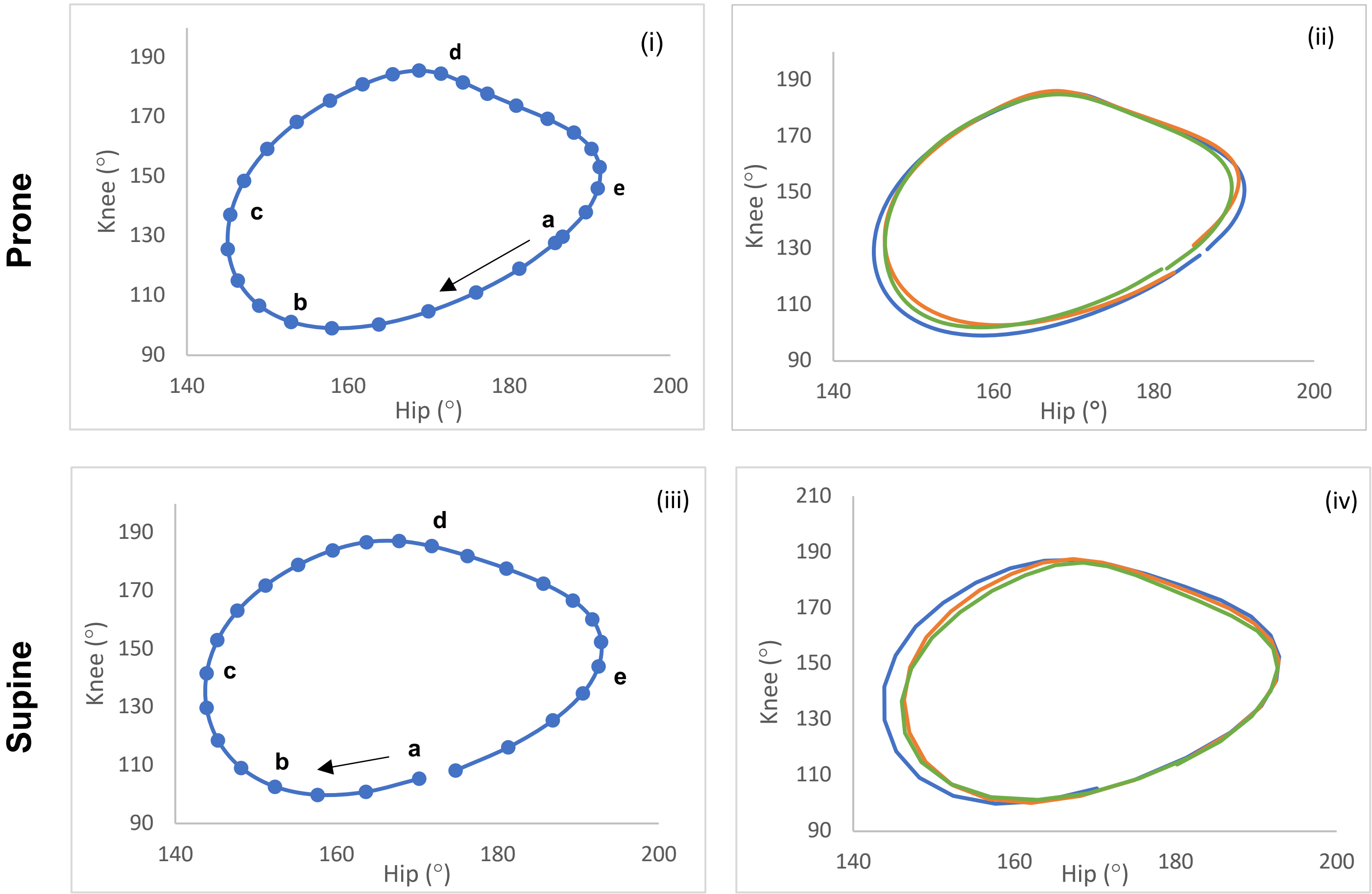


Figure 7.5. Hip and knee angle-angle plot for the slowest male kicker for (i) one prone kick cycle, (ii) three consecutive prone kick cycles, (iii) one supine kick cycle, and (iv) three consecutive supine kick cycles. Blue line represents kick cycle one, orange line represents kick cycle two, green line represents kick cycle three.

Reading Figure 7.5 (i) and (iii) clockwise, between *a* and *b*, both the hip and knee were flexing; between *b* and *c* the hip continues to flex but the knee extends. After *c*, both the hip and knee extend until *d*, after which point the knee flexes. The hip continues to extend, however, until *e*, from which point both the hip and knee flex again. The plots for prone and supine kicking are similar topologically, yet this swimmer demonstrated a longer period of hip and knee flexion at the start of the kick cycle during prone kicking (i) than supine kicking (iii). From Figure 7.5 (ii) and (iv), it can be seen that there is not much intra-individual variation between kick cycles; however, there was slightly more variation for supine kicking than prone.

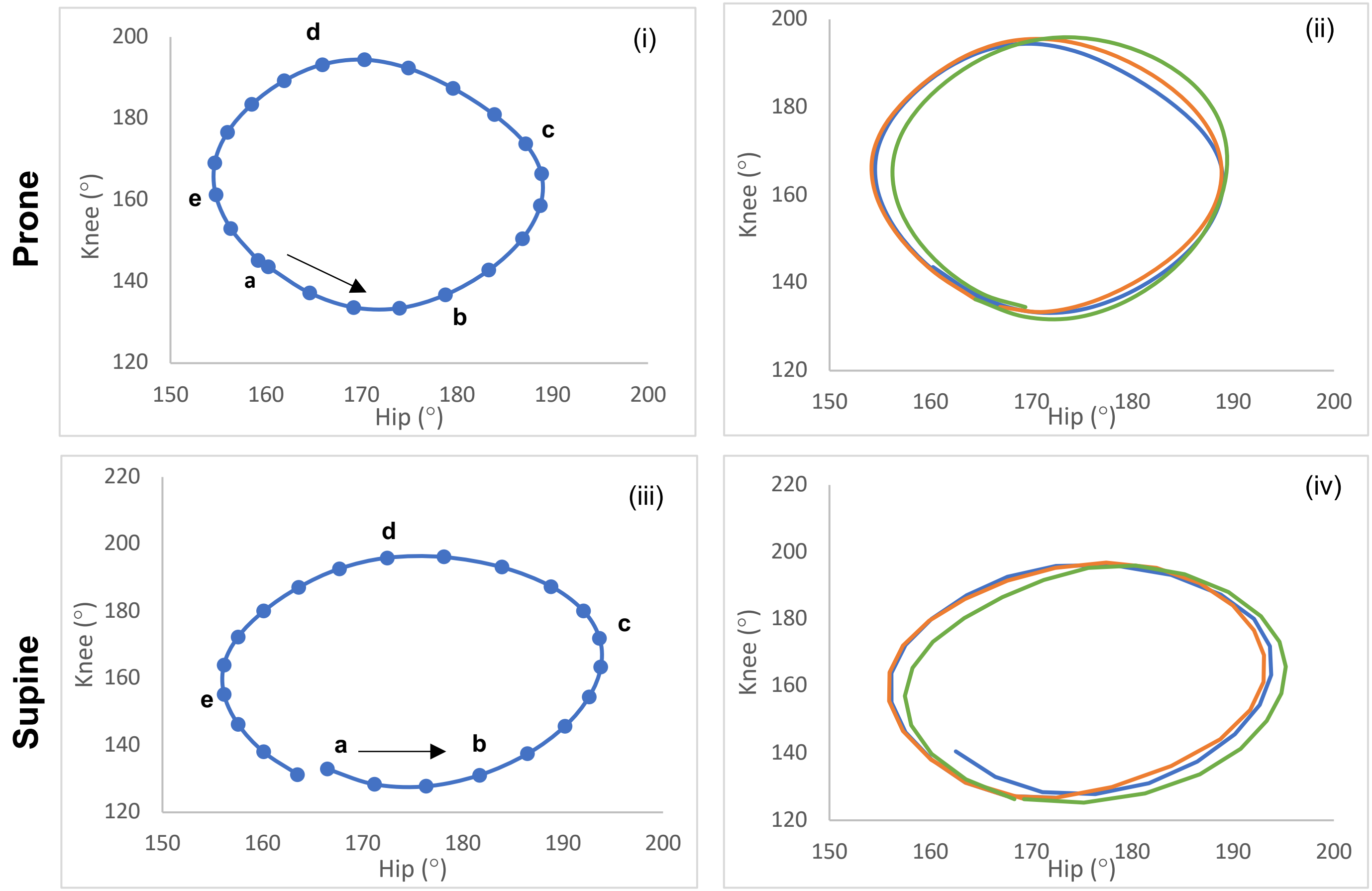


Figure 7.6. Hip and knee angle-angle plot for the slowest female kicker for (i) one prone kick cycle, (ii) three consecutive prone kick cycles, (iii) one supine kick cycle, and (iv) three consecutive supine kick cycles. Blue line represents kick cycle one, orange line represents kick cycle two, green line represents kick cycle three.

Reading Figure 7.6 (i) and (iii) anti-clockwise, between *a* and *b*, the hip extends while the knee briefly flexes; after *b*, both the hip and knee are extending. Between *c* and *d*, the knee continues to extend whilst the hip flexes. The knee and hip both flex after *d*, until *e*, when the hip extends whilst the knee flexes. This is a different pattern from the other three swimmers discussed; there is no period of hip flexion at the beginning of the cycle. Additionally, the plots for prone (i) and supine (iii) kick for this swimmer are different from each other. The line between *a* and *b* for prone kicking (i) is steeper than that for supine kicking (iii); this indicates the knee was flexing faster than the hip was extending for prone UDK, whereas for supine UDK the hip was extending faster than the knee was flexing. Further, the line between *c* and *d* is also steeper for prone kicking than supine kicking. This indicates the knee was extending faster than the hip was flexing for prone UDK, whereas for supine UDK the hip was flexing faster than the knee was extending.

7.3.3. CRP

Table 7.3. Continuous relative phase values for the hip/knee coupling for the start, end, and transition points in the kick cycle, the mean over the knee extension and knee flexion phases, and the between-cycle standard variation within those phases (mean ± SD). * represents a significant difference between sexes.

Hip/Knee		**CRPstart (°)**	**CRPend (°)**	**CRPtransition (°)**	**CRPext (°)**	**CRPflex (°)**	**SDext**	**SDflex**
Prone UDK	Male (n=9)	64.0 ± 10.3	57.1 ± 14.7	91.5 ± 11.8	62.8 ± 6.1	57.4 ± 9.5	8.4 ± 2.7	10.8 ± 5.4
	Female (n=5)	49.0 ± 32.4	48.1 ± 22.7	69.3 ± 25.3	62.5 ± 6.7	68.3 ± 12.8	12.1 ± 4.2*	11.5 ± 2.5
	All (n=14)	58.6 ± 21.1	53.9 ± 17.7	83.6 ± 20.2	62.7 ± 6.1	61.3 ± 11.6	9.7 ± 3.6	11.1 ± 4.5
Supine UDK	Male (n=9)	57.9 ± 14.4	59.7 ± 11.2	98.4 ± 27.0	66.1 ± 8.9	58.5 ± 13.5	9.1 ± 2.8	11.1 ± 3.7
	Female (n=5)	47.6 ± 16.8	53.8 ± 29.2	69.1 ± 27.1	62.8 ± 5.3	65.5 ± 9.2	10.3 ± 3.9*	9.6 ± 2.0
	All (n=14)	54.2 ± 15.5	57.6 ± 18.7	87.9 ± 29.8	64.9 ± 7.7	61.0 ± 12.2	9.5 ± 3.1	10.6 ± 3.2

Table 7.4. Continuous relative phase values for the knee/ankle coupling for the start, end, and transition points in the kick cycle, the mean over the knee extension and knee flexion phases, and the between-cycle standard variation within those phases (mean ± SD).

Knee/Ankle		**CRPstart (°)**	**CRPend (°)**	**CRPtransition (°)**	**CRPext (°)**	**CRPflex (°)**	**SDext**	**SDflex**
Prone UDK	Male (n=9)	37.3 ± 20.2	44.8 ± 19.1	87.2 ± 34.2	72.3 ± 4.5	95.2 ± 28.3	14.5 ± 7.0	12.2 ± 6.7
	Female (n=5)	32.7 ± 23.3	25.3 ± 6.4	101.1 ± 52.6	71.8 ± 6.3	98.4 ± 9.9	15.4 ± 4.4	12.9 ± 3.1
	All (n=14)	35.7 ± 20.6	37.8 ± 18.2	92.2 ± 40.2	72.1 ± 5.0	96.4 ± 23.0	14.8 ± 6.0	12.5 ± 5.6
Supine UDK	Male (n=9)	49.8 ± 16.7	34.0 ± 24.5	113.5 ± 33.1	73.9 ± 10.4	103.1 ± 16.4	13.3 ± 11.2	11.2 ± 2.6
	Female (n=5)	27.0 ± 19.3	29.6 ± 14.2	109.5 ± 28.4	70.6 ± 6.4	91.0 ± 15.1	7.5 ± 3.4	9.4 ± 1.7
	All (n=14)	41.6 ± 20.4	32.4 ± 20.9	112.1 ± 30.4	72.8 ± 9.1	98.7 ± 16.5	11.2 ± 6.2	10.6 ± 2.4

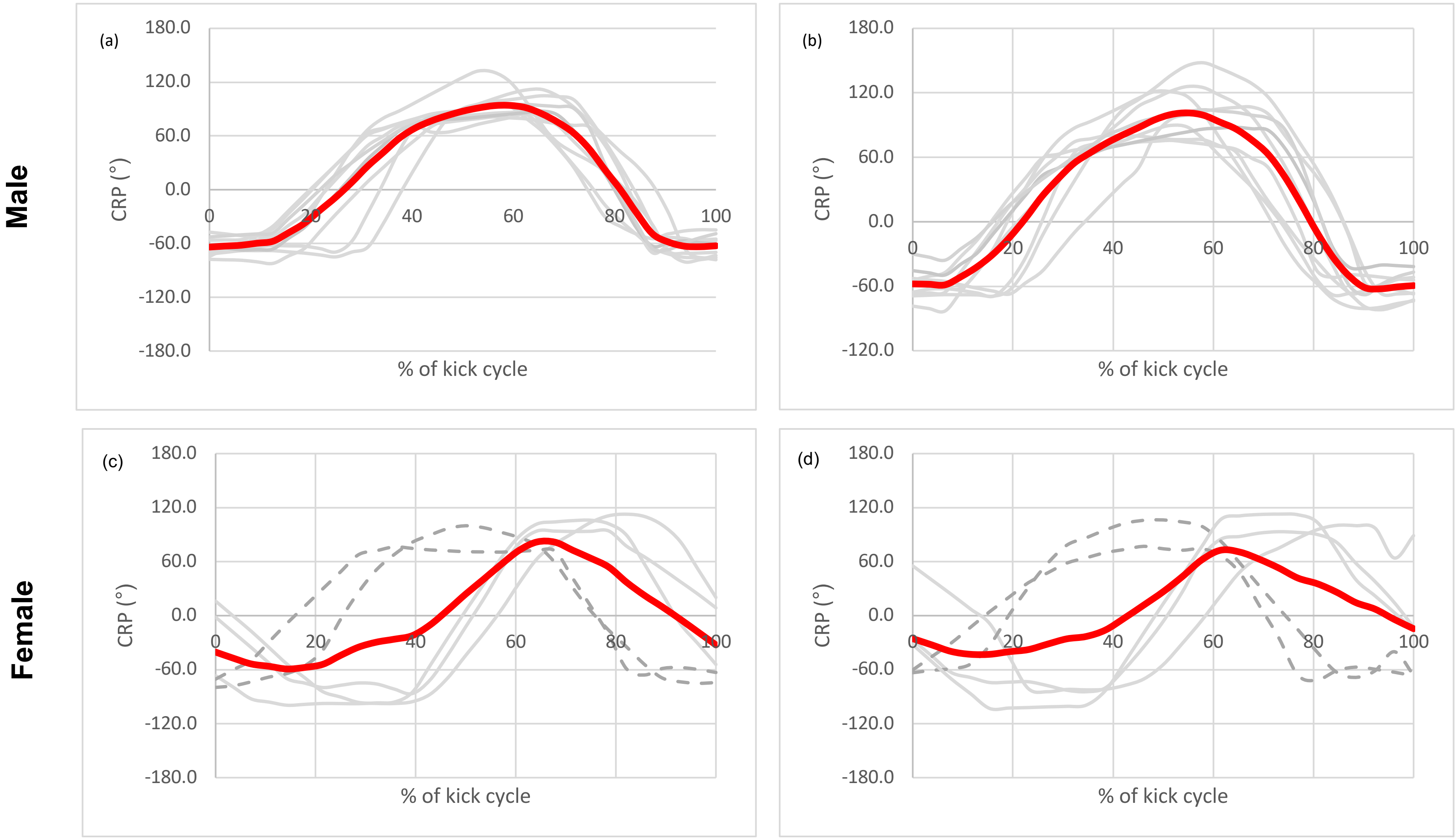


Figure 7.7. Ensemble CRP curves for the hip/knee coupling normalised to percentage of kick cycle for (a) male prone UDK, (b) male supine UDK, (c) female prone UDK, and (d) female supine UDK. Grey lines represent individual participants' ensemble CRP curves; the red line denotes the group mean ensemble curve across all participants. The two dashed lines indicate the two female outliers. 0% of kick cycle denotes the start of the knee extension phase.

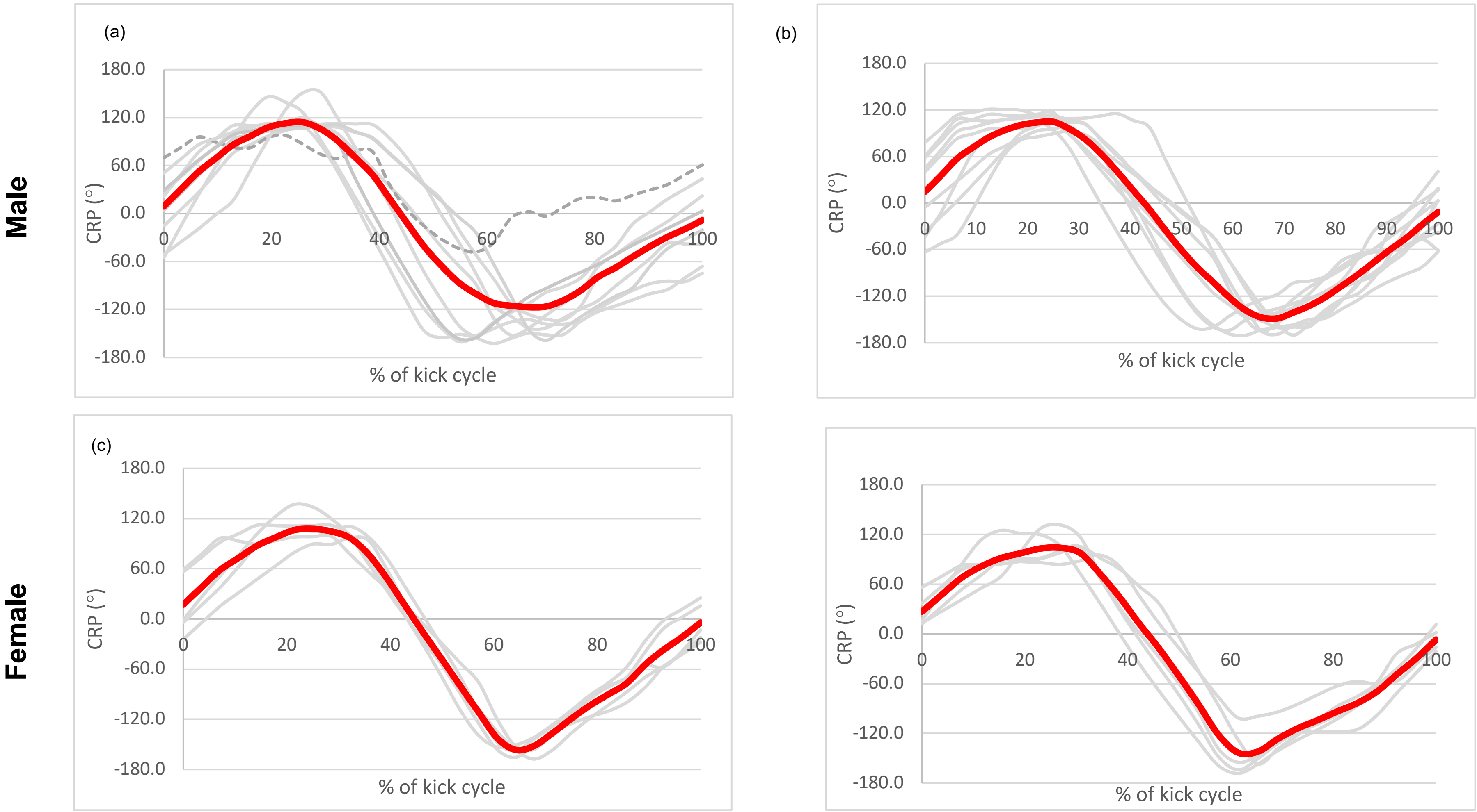


Figure 7.8. Ensemble CRP curves for the knee/ankle coupling normalised to percentage of kick cycle for (a) male prone UDK, (b) male supine UDK, (c) female prone UDK, and (d) female supine UDK. Grey lines represent individual participants' ensemble CRP curves; the red line denotes the group mean ensemble curve across all participants. 0% of kick cycle denotes the start of the knee extension phase.

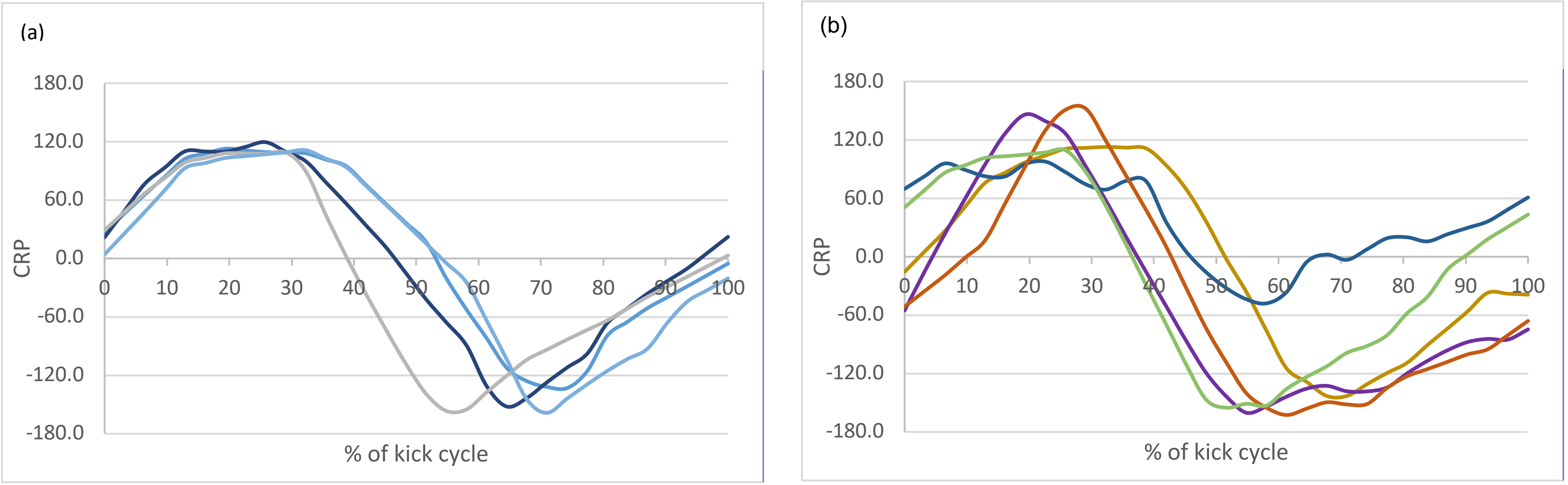


Figure 7.9. Individual participant CRP curves for the knee/ankle coupling during prone UDK for (a) the fastest four male kickers, and (b) the slowest five male kickers. 0% of kick cycle denotes the start of the knee extension phase.

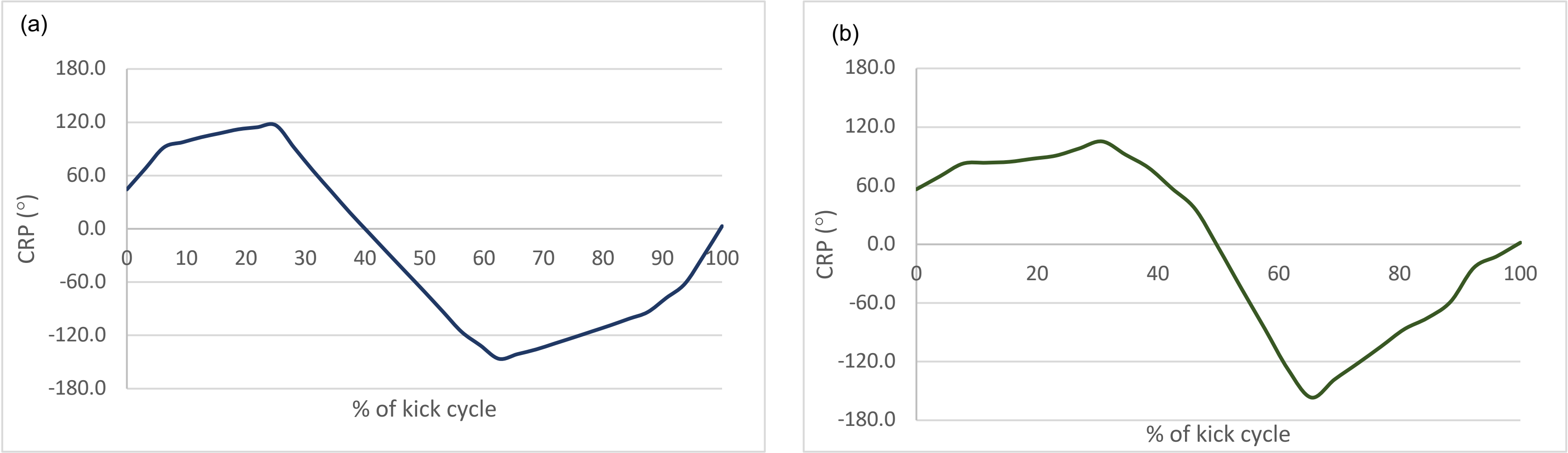


Figure 7.10. Individual participant CRP curves for the knee/ankle coupling during supine UDK for (a) the fastest male kicker, and (b) the fastest female kicker. 0% of kick cycle denotes the start of the knee extension phase.

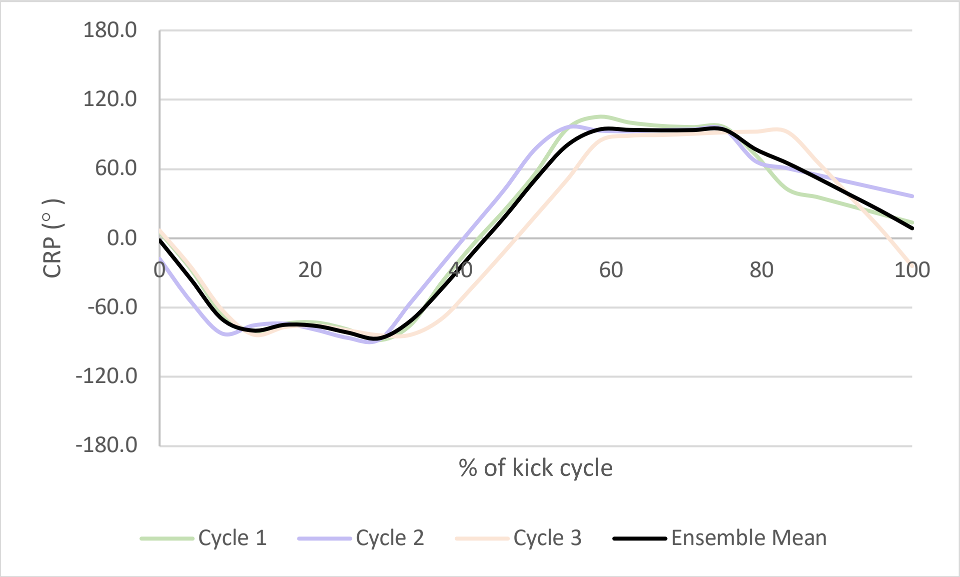


Figure 7.11. CRP curves for the hip/knee coupling of three consecutive kick cycles and ensemble mean of one female participant for prone UDK, demonstrating between-cycle variability. 0% of kick cycle denotes the start of the knee extension phase.

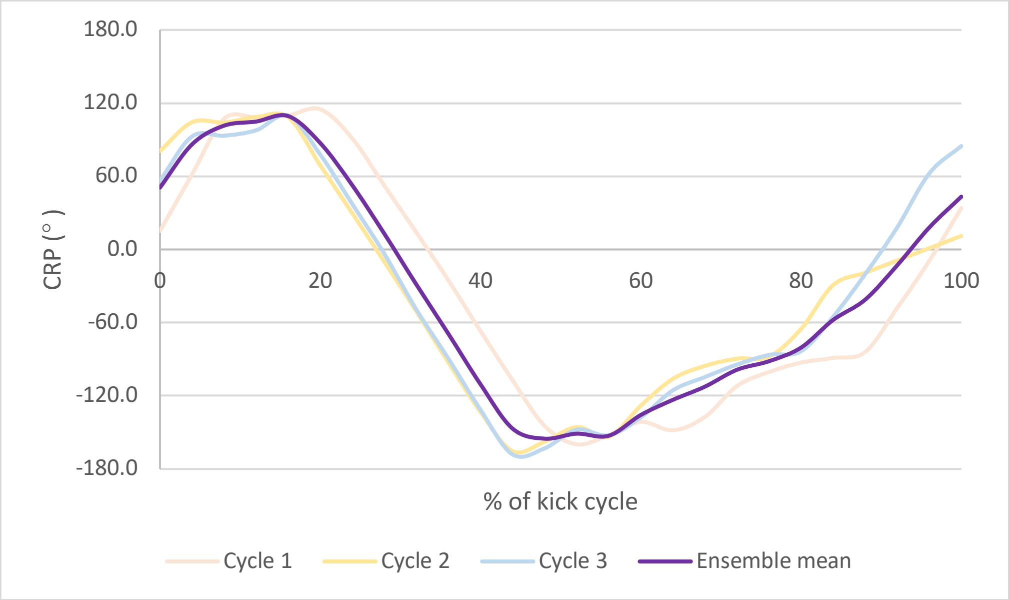


Figure 7.12. CRP curves for the knee/ankle coupling of three consecutive kick cycles and ensemble mean of one male participant for prone UDK, demonstrating between-cycle variability. 0% of kick cycle denotes the start of the knee extension phase.

Hip/Knee

For the hip/knee coupling, a significant main effect of orientation with a large effect size was found for SDext ($F_{(1,12)} = 11.5$, $P = .005$, $\eta^2_p = .49$); the female swimmers demonstrated significantly more between-cycle variation in the knee extension phase than the male swimmers. No significant interactions or other main effects were found for the hip/knee coupling.

Knee/Ankle

No significant main effect of orientation or sex was found for the knee/ankle coupling.

7.4. Discussion

The aims of this study were to determine if movement patterns in UDK demonstrated a temporal sequence in both phases of the kick cycle, to determine if differences existed in coordination between prone and supine UDK and by males and females, and to identify if faster kickers demonstrated more variability in coordination than slower kickers. It was first hypothesised that a temporally sequential movement pattern would be observed for the knee extension phase of the kick cycle, but not the knee flexion phase. However, sequential patterns were found for the knee flexion phase in supine UDK for both males and females, and for males in prone UDK. Further, neither kick orientation showed a temporally sequential pattern for the knee extension phase of the kick, in either men or women. Consequently, this hypothesis was rejected. The second hypothesis was that differences would exist in coordination between prone and supine UDK. However, no statistically significant differences were found in CRP between prone and supine UDK; thus, this hypothesis was also rejected. Finally, it was hypothesised that differences would exist in coordination between males and females performing UDK. No significant differences were found for the knee/ankle coupling; however, the females demonstrated significantly larger between-cycle variation for the hip/knee coupling than did the males. As such this hypothesis was accepted.

7.4.1 Temporal analysis

It was hypothesised that the knee extension phase of UDK would demonstrate a sequential movement pattern; this was not found to be the case in the present study, indeed the opposite pattern was observed. This was unexpected, as the knee extension phase is often the more propulsive of the two, with only skilled kickers able to produce similar levels of propulsion from both phases of the kick (Arellano *et al.*, 2002; Atkison *et al.*, 2014; Connaboy *et al.*, 2009). As such, it was anticipated that this phase would be sequential in order to successfully transfer momentum down the kinetic chain. That this was not observed may indicate that evaluating the occurrence of maximum vertical velocity of each segment may not be the most effective method of quantifying coordination in UDK. It can provide some information on the coordination patterns of skilled kickers, yet additional analysis may be required to comprehensively understand underlying mechanisms. Additionally, it may be that traditional application of the summation of speed principle may not be valid in this instance. Due to the nature of applying force in an aquatic medium, some momentum will inevitably be transferred to the water, and thus will not be conserved within the kinematic chain. Further research is required to ascertain this.

Sequential patterns were observed in the knee flexion phases of both supine and prone UDK for both sexes combined. When assessing the female swimmers independently, however, the foot reached maximum velocity just prior to the shank, and the timings for the thigh, shank, and foot were very close together. From these data, an almost synchronous pattern for the segments of the lower limb can be inferred. This sequence demonstrated a suboptimal momentum transfer along the kinematic chain. For this transfer to successfully take place, one segment would be required to slow down, thereby losing momentum, as the adjacent segment gains that momentum and consequently speeds up. As such, it was expected that the more proximal segments of the body would reach their maximum velocity first, and each contiguous segment along the chain would follow, thus demonstrating a temporal sequence. However, the lower limb segments reached maximum velocity almost at once, indicating that this transfer of momentum did not take place for the female swimmers. This progression of momentum along the body has been shown to be key to performance (Higgs *et al.*, 2007; Hochstein and Blickhan, 2011), and is considered an important condition for the shedding of powerful vortices required for propulsion (Arellano *et al.*, 2002). Consequently, the pattern demonstrated by the females could be suggested to be less effective than the males. The discrepancy between sexes may be due to many reasons, such as a comparatively lower hamstring strength for the females than the males. Males have been found to produce greater peak torque in the quadriceps and hamstrings than females (Campenella *et al*., 2000), suggested to be attributed to differences in morphology, most notably a larger percentage of lean muscle mass, greater cross-sectional area, and larger type I and type II fibres (Miller *et al*., 1993). Previous research (Higgs *et al*., 2017; Yamakawa *et al*., 2018) as well as Chapter Six of this thesis demonstrated that knee flexion velocity and hip extension velocity are key to UDK performance. As the hamstrings are integral to both movements, a comparatively lower hamstring strength for the female athletes than the males could compromise performance. Alternatively, it could simply be that a proximal-to-distal sequence is not the optimal strategy for this kick phase. However, when examining individual temporal patterns, it appears that the fastest female swimmer did demonstrate a proximal-to-distal sequence. Given that her mean speed was 0.36 $m.s^{-1}$ faster than the rest of the group, and that the fastest male swimmers also demonstrated this pattern, a proximal-to-distal sequence of segments is recommended to ensure fast UDK. As such, the slower kickers could focus on ensuring their movement of segments is sequential over the knee flexion phase.

For supine UDK for the female swimmers, the foot reached maximum velocity first. As indicated previously, many swimmers will emphasise the knee extension phase, either through a specific technique or the anatomical limitations previously discussed (Atkison *et al*., 2014; Hochstein and Blickhan, 2011). In doing so, the movement of the lower leg may be prioritised. This may arise as a consequence of a restriction in mobility, for example, a limited range of hip extension. The movement and velocity of the hip has been shown to be related to UDK performance, both in previous literature (Higgs *et al*., 2017; ; Yamakawa *et al*., 2018) and in Chapter Six of this thesis. With a reduction in hip mobility, the athlete may need to rely on other joints further down in the chain to drive propulsion. As a result, the ‘body wave’ would not move successively down the kinematic chain. Alongside maximum vertical toe velocity, body wave velocity has been found to be a strong predictor of human UDK performance (Higgs *et al*., 2017; Hochstein and Blickhan, 2011). Therefore, ensuring a temporally sequenced transfer of momentum towards the toes facilitates effective UDK. As such, the mean temporal pattern demonstrated by both sexes could be less effective than if the segments’ velocities progressed sequentially.

It is possible that the swimmers were not maximising the use of the ankle, meaning the movement was predominantly driven by the knee (Willems *et al*., 2014). Deliberate and consistent dorsi- and plantar-flexion is a key component of fast UDK, as it ensures the powerful 'whip-like' action required to create larger rotating vortices and therefore maximise propulsion (Arellano *et al*., 2002; Gavilan *et al*., 2006). Alternatively, restrictions in the transfer of momentum along the kinematic chain may arise due to incorrect timing of segments and muscle activation. Due to the order that the segments reached maximum velocity for both segments, i.e., culminating in the trunk then thigh, this could indicate ineffective musculoskeletal coordination around the pelvic-lumbar area for this cohort. However, inferences of this nature are beyond the scope of this study, and require an investigation into the muscular activation patterns of the main muscle groups responsible for UDK. An examination of the activity of the muscles driving these movements may help elucidate why a proximal-to-distal sequence was not found for the knee extension phase of the kick cycle.

7.4.2 CRP

7.4.2.1 Hip/knee

The CRP for the hip/knee coupling describes the relative phase between these two joints at any given point over the kick cycle. In the context of UDK, it refers to the degree to which the two joints are flexing or extending simultaneously (in-phase) or sequentially (out-of-phase). As discussed, a temporally sequential movement of segments is considered to be required to transfer momentum along the body and ultimately to the water (Wang and Liu, 2006; Higgs *et al*., 2017). For optimum propulsion, this oscillation of segments should be continuous in both directions. As such, it was not expected that the joints involved in either coupling (hip/knee or knee/ankle) would ever be perfectly in-phase, as represented by a CRP of 0°. However, out-of-phase coordination is likely more effective than in-phase, demonstrating the coupling of, as an example, hip extension and knee flexion. This was confirmed in the mixed ANOVA results of the present study. Though CRP values never reached a state of complete anti-phase, indicated by a CRP of 180°, the coordination mode for the hip/knee coupling was certainly out-of-phase on average for both males and females kicking supine and prone (Table 7.3). Further, though it was hypothesised that there would be differences in CRP values between prone and supine kicking, no statistically significant results were found for the hip/knee coupling.

The female swimmers demonstrated more intra-individual variation than did the male swimmers, for both kicking orientations. Within the context of DST, variability is not considered to be inherently positive or negative to performance, but simply an indication of the array of movement patterns used to complete a given task (van Emmerik *et al*., 2014). Large amounts of variability could represent a change in phase or movement pattern (Stergiou *et al*., 200; van Emmerik *et al*., 2014), and may indicate a skilled performer's capacity to adapt their movement pattern to maintain the desired performance outcome (Davids *et al*., 2008). Figure 7.11 demonstrates the CRP curves for one female participant kicking prone. For 30% of the kick cycle, the majority of the knee extension phase, there is little variability of the CRP, with the curves appearing quite similar. However, between 30% and 60% of the kick cycle, there is relatively high intra-individual variation evident. As the transition between knee extension phase and knee flexion phase occurred at 52% of the kick cycle for this athlete, this period represents the overlap of one phase ending at the same time as the other phase is beginning. Kick cycle 3 differs to kick cycles 1 and 2, in that the transition towards more in-phase coordination at around 30-40% of kick cycle occurs slightly later for kick cycle 3. This possibly indicates that the system made an adjustment as a result of a perturbation or incoming information. For example, this may have been an increase in drag experienced by the swimmer, and a consequential attempt to adjust movement so as to maintain speed. Following a brief period of reduced variation between 60% and 70% of kick cycle, variability again increases throughout the knee flexion phase. These periods of higher variation may, therefore, be an example of compensatory variability, in which the specific movement and interaction of joints along a kinematic chain are organised to ensure a consistent performance outcome (Robins, 2013). It could be that the variability observed in different time points throughout the kick cycle were an attempt to ensure a consistent performance at the system level. This is only one example from the female athletes; however, similar periods of variability were also observed for the rest of the group.

The movement pattern for the female group was more variable than that for the male group. This could be for a multitude of reasons. It may indicate that the movement pattern for the females is less able to withstand fatigue than that of the male swimmers. The three kick cycles used for the CRP analysis were taken from the beginning of the underwater phase, excluding the first two kicks so as to eliminate the effect of pushing off the wall. Consequently, it may be suggested that fatigue is not likely to have a large effect on performance; however, it may play some part in repeated maximal efforts. Alternatively, the larger variation may be indicative of the discrepancy between the movement pattern required to ensure the intensity requested for the maximal effort trials compared with what is considered ‘normal’ for that athlete. For example, a 200 m swimmer’s underwater phase may usually be focused more upon ensuring efficiency, rather than maximum speed. As such, a switch of focus to maximum speed may have resulted in different and more variable movement patterns due to an imposed task constraint.

Examining Figure 7.7, it can be seen that the males begin and end the kick cycle slightly more out-of-phase than the females for both prone and supine. However, for both sexes, CRP was more in-phase at the start and end of kick cycle than in the middle. Given that the transition between knee extension and knee flexion phase occurred at 51% and 52% of the kick cycle for the males during prone and supine kicking respectively, CRP for that group was most out-of-phase during the knee flexion phase of the kick cycle. This corresponds to the findings of the temporal analysis, indicating that this phase was more sequential than the knee extension phase for this cohort. It is also evident from Figure 7.7 that the mean ensemble curve for the men is representative of the group, as the individual participant ensemble curves do not differ greatly from the mean curve. Conversely, the female swimmers do not all follow the same curve shape as the mean; there are two female swimmers who demonstrate maximum out-of-phase CRP earlier in the cycle for both kicking orientations (identified by the dashed lines). As such, the female swimmers exhibited more inter-individual variability, as well as intra-individual. The two swimmers whose maxima occurred earlier in the kick cycle were the fastest two kickers in supine UDK, and within the top three fastest for prone kicking. Their period of most out-of-phase coordination begins in the knee extension phase and almost plateaus until after the transition into the knee flexion phase, at which point CRP values start to decrease. This is in contrast to the rest of the women, who demonstrated a different shaped curve, due to a period of hip extension between approximately 0% and 40% of kick cycle. A delayed initiation of hip flexion may be due to an ineffectual sequencing of segments. The consequential reduction in performance is exhibited by the lower UDK speeds of these female athletes, compared with the faster athletes of the cohort that did not demonstrate this period of hip extension at the beginning of the kick cycle.

The males did not demonstrate as much inter-individual variation for the hip/knee coupling as the females did. Additionally, the males were fairly homogenous at the beginning and end of the kick cycle in both kicking orientations, yet demonstrated much more inter-individual variation in the middle of the kick cycle. This may be reflective of the system's capacity to adjust and correct for errors at individual joints along the chain to ensure consistency at the start and end of a movement pattern (Latash, 2000). In this way, variability is smaller at the end-point of the movement than at other points in the kinematic chain. This phenomenon was first demonstrated by Bernstein (1924) who observed that the variability of the tip of a blacksmith's hammer was lower than that of the joints further up the chain within the arm (Bernstein, 1924, cited in Latash, 2000). This is suggested to indicate that joints or segments act in partnership to correct errors and preserve a consistent performance outcome (Latash, 2000; Robins, 2013). This concept of variation funnelling down to ensure a consistent performance outcome has previously been suggested to occur in UDK by Hochstein and Blickhan (2014), who found asymmetric joint amplitudes along the body, but that the feet move almost symmetrically. Therefore, the segments of the body must be coordinated effectively to ensure this symmetry of the end-effectors. Similarly to the fastest females, the men began and ended the kick cycle relatively in-phase, and reached maximum out-of-phase in the middle of the kick cycle. For both kicking orientations, this occurred in the knee flexion phase. The relatively more in-phase CRP at the beginning of the kick cycle reflects the slight period of hip and knee flexion at the beginning of the kick cycle demonstrated in the angle-angle plots. The subsequent shift in CRP towards maximum out-of-phase coordination reflects the change in direction of the knee, as it begins to extend, continuing until after the transition point into knee flexion phase. At this point, the hip begins to extend, followed by the knee commencing its flexion phase. As this occurs, the joint coupling shifts slowly back into a relatively more in-phase pattern, until approximately 80% of the kick cycle. At this point, the CRP returns to a similar state as at the beginning of the kick cycle. That the fastest kickers, both male and female, demonstrate this curve is likely indicative of this being a recommended pattern for success in UDK. In contrast, the slowest female swimmer's hip/knee coupling is almost completely in-phase at the beginning and end of the kick cycle with two periods of extreme out-of-phase movement in the kick cycle. This could indicate that the swimmer’s timing of coordination of the hip and knee is ineffective and that the wave is not progressing successfully through the kinematic chain.

7.4.2.1 Knee/ankle

In agreement with the mixed ANOVA results of the hip/knee coupling, no statistically significant differences were found between prone and supine UDK for this cohort. Additionally, no significant differences were found between males and females. This was unexpected, particularly following the results of Chapter Six of this body of work which demonstrated differences between the kinematic parameters of UDK by males and females. However, despite no statistical differences found for any CRP parameters, Table 7.4 demonstrates there were subtle differences between groups. For example, for CRPstart, coordination was more out-of-phase for supine UDK than prone for the entire participant group; additionally, whilst values between males and females were similar for CRPstart in prone kicking, males were more out-of-phase than females in supine UDK by 22.8°. Further, males were more out-of-phase than females for CRPend in both prone and supine UDK. Critically, however, CRP is a continuous measure; therefore, the lack of statistical significance in discrete CRP parameters does not exclude distinctions in overall coordination mode over the kick cycle between participants. Such distinctions can be identified by examining the CRP curves themselves.

Mean CRP values were higher for the knee flexion phase than the knee extension phase, for both sexes in both kicking orientations, indicating a more out-of-phase mode of coordination. This was unexpected, yet is in agreement with the temporal analysis results of this study. Interestingly, however, the standard deviation values for CRPflex were mostly much higher than those for CRPext, demonstrating a larger amount of inter-individual variation for this phase of the kick cycle. This variability can be seen in Figure 7.8, and is most pronounced for the males. For prone kicking, though most of the participants’ individual traces follow a similar curve to the mean ensemble curve, there are distinct differences in where many of them reach maxima or minima (Figure 7.8 [a]). The exception to this is one outlier, identified by the dashed lines. As can be seen from the Figure, this curve differs greatly from the mean ensemble curve for this group, with the coordination mostly more in-phase during the knee flexion phase of the kick cycle. Indeed, the variability for this group in the knee flexion phase is striking, with nearly all the participants reaching minima at different times in the kick cycle, between approximately 50% and 70% of kick cycle. This point of maximal out-of-phase movement in the knee flexion phase represents the point at which the knee switches from maximal extension and begins flexing in earnest. As demonstrated by Figure 7.8 (a), for some participants this occurred almost immediately after the transition point between kick phases, yet for others it did not occur until nearly mid-way through this second phase. These variations in CRP traces indicate different movement solutions to the same task, and demonstrate the inter-individual nature of coordinative strategies. An individual's movement pattern is determined by the interaction of organismic, task, and environmental constraints, many of which will be specific to them (Davids *et al*., 2008). As such, though common patterns may be identified amongst particularly homogenous groups, the between-participant variation displayed in Figure 7.8 further substantiates that analysis of coordination ought to be performed on a bespoke basis for the athlete in question (Nikodelis *et al*., 2013).

The between-participant variation displayed by the males for the knee/ankle coupling enables the identification of aspects to the movement pattern common amongst different skill levels. For example, the top four fastest male kickers were very homogenous for the first 30% of the kick cycle, beginning the kick cycle in a relatively in-phase state and rising to a plateau of around 100° lasting from 10% to 30% of the kick cycle. This period represents the initial period of knee flexion alongside the ankle moving into its maximal plantar-flexed position. The change in direction of the curve at 30% of kick cycle denotes the ankle switching to a more dorsi-flexed position whilst the knee moves through extension. At this point, for these swimmers, there is more variation, continuing until the minimum CRP point of around 150° (Figure 7.9 [a]). This minimum point represents the time at which the knee switches to flexion and occurs at different times for the swimmers. Interestingly, the two fastest kickers, both of whom were international level, had this switch at around 65-70% of kick cycle; in contrast, the two national swimmers switched to knee flexion either earlier (at around 50% of kick cycle) or later (around 75% of kick cycle) than the two international swimmers. Consequently, the international swimmers likely had a longer period of knee extension than did the national swimmers.

Two of the male participants have higher and narrower maxima within the knee extension phase. This part of the curve represents the point of maximal plantar-flexion of the ankle, and the point at which it begins to fall back towards 0° indicates the moment the ankle switches to dorsi-flexion. Consequently, it appears that these participants had a shorter time period of plantar-flexion. This could be disadvantageous as maximum plantar-flexion has been found to be related to UDK performance, both in previous literature (Atkison *et al*., 2014) and in Chapter Six of this thesis. That the two slowest male kickers demonstrated this shorter period of plantar-flexion and abrupt switch to dorsi-flexion could suggest that this is an ineffective movement pattern for UDK performance. As such, it may be inferred that, for better UDK performance, it is preferential to have both a sustained period of plantar-flexion and knee extension, highlighted by the initial plateau at the beginning of the kick cycle, and the later transition to knee flexion by the fastest male kickers.

When considering the slowest five male kickers in isolation, large amounts of inter-individual variation in the knee flexion phase can be seen, with average CRP values over the phase ranging from 125° to 27° for these five participants (Figure 7.9 [b]). Furthermore, these participants also began and ended the kick cycle in a more out-of-phase state than did the fastest four kickers. A possible reason for this discrepancy is due to the timing of the two joints. It appears more advantageous to have a fast plantar-flexion velocity at the start of the kick cycle, and initiate knee extension at around 15% of the kick cycle. In contrast, the slowest male kicker demonstrated a slower plantar-flexion velocity to reach maximal plantar-flexion, as indicated by the maximum CRP value occurring at 30% as opposed to the plateau reached at around 10% by the fastest male kicker. Additionally, the slower kicker’s knee extension did not commence until approximately 22% of the kick cycle, and ended at around 65% of the kick cycle. The slower plantar-flexion velocity and comparatively shorter period of knee extension for the slower kicker than the faster kicker could indicate an ineffective coupling between the knee and ankle for this swimmer.

For the male swimmers in supine UDK, large amounts of inter-individual variation were found during the first 20% of the kick cycle (Figure 7.8 [c]). Of note is that, despite these discrepancies at the beginning of the kick cycle, nearly all the curves have their maximum CRP at around 25% of kick cycle. As discussed above, this peak and subsequent change of direction towards 0° represents the switch of the ankle from a plantar-flexed position towards a dorsi-flexed position, at the same time that the knee is at the beginning of its extension. Consequently, even though there are differences in knee/ankle coupling during the first 20% of the kick cycle, it appears that dorsi-flexion at 25% of kick cycle is a common feature of this movement pattern. Thereafter, the group again demonstrates considerable inter-individual variation; in a similar manner to prone UDK, the time at which the athletes switched to knee flexion varies. As with prone UDK, the fastest kicker does so at around 65%, and the slowest kicker earlier than this, at around 59%. Whilst there are definite differences amongst the group in CRP values during the knee flexion phase, with some participants more in-phase than others during this part of the kick cycle, the variability is not as large as for prone UDK. With the exception of one athlete whose ankle does not switch until around 40% of the kick cycle, there is mostly one common movement pattern for the knee/ankle coupling for the male participants in supine UDK.

The female swimmers, in contrast to the males, were fairly homogenous in CRP for the knee/ankle coupling in both kicking orientations. As can be seen from Figure 7.8 (b) and (d), there was more inter-individual variation in supine UDK than prone UDK, again contrasting with the male swimmers. However, the majority of the variability within the group during prone UDK arose from the first 30% of the kick cycle, which was similar to the male athletes. The fastest male and fastest female kicker in this study demonstrated almost identical CRP curves for the knee/ankle coupling during prone UDK (Figure 7.10). The fastest female kicker's curve begins slightly more out-of-phase than the fastest male kicker, yet contains a similar plateau between 5% and 30% of the kick cycle, followed by a comparable slope downwards until around 65% of the kick cycle, at which point the curve changes direction as the knee begins to flex. A similar comparison was demonstrated in supine UDK between these swimmers. It would therefore seem that this is a particularly advantageous movement pattern for high UDK performance. However, this must be taken in context with regards to the swimmers' interaction with both organismic and task constraints. The UDK technique of these two swimmers is characterised by a higher frequency, lower amplitude approach. They are smaller in stature and build than other elite kickers not included within this study, who may instead favour a higher amplitude, lower frequency technique. Consequently, whilst these results offer novel insight into the coupling between the knee and the ankle during maximal UDK, there may well be other movement patterns equally effective at producing high performance.

Alongside inter-individual variation, there were also differences found in intra-individual variation in the present study as demonstrated by between-cycle standard deviations. There was more intra-individual variation by both sexes in prone UDK than in supine UDK; additionally, the female swimmers demonstrated more variability in prone kicking, yet the male swimmers did in supine kicking. A particularly variable example can be seen in Figure 7.12, comprising the CRP for the knee/ankle coupling during prone UDK for one male swimmer. There are periods where the three kick cycles are similar or cross over one another, but there are also large periods of variability. Strikingly, the downward slope between 20% and around 45% of kick cycle that represents the majority of the knee extension varies considerably, with the first kick cycle relatively more in-phase than the second and third kick cycle. Interestingly, the transition from knee extension to knee flexion is fairly consistent, yet considerable intra-individual variation is again present for the knee flexion phase. Contrastingly, the first kick cycle is more out-of-phase than the other two kick cycles during this stage. As discussed previously, this variability is not intrinsically good or bad and does not indicate a presence or absence of higher ability within a specific skill, exemplified by the fact that the slowest male kicker exhibited very consistent technique between kick cycles. Instead, it likely indicates an effect of one or more constraint on action, with the interaction of these helping to determine the extent of movement variability (Robins, 2013). It may be that the system adapted in response to various informational constraints, such as an increase in drag or a change in depth under the water as the swimmer moved closer towards the surface ready to breakout. Additionally, the adjustment in movement pattern may be reflective of the change in kinematics over the underwater phase outlined in Chapter Six. This particular swimmer's horizontal COM speed decreased by 25% over the underwater phase, thus these changes in movement pattern between kick cycles could reflect this decrease in performance over time.

7.5. Conclusion

This study attempted to identify and describe coordination patterns of elite swimmers performing maximal UDK, and compare such patterns between male and female swimmers when kicking prone and supine. It was determined that, for this cohort, a temporally sequential pattern existed for the knee flexion phase, but not the knee extension phase. However, coordination modes between the hip and knee, and knee and ankle, do not appear to differ significantly between prone and supine kicking. However, female swimmers demonstrated larger intra-individual variability than did male swimmers for the hip/knee coupling, and large amounts of inter-individual variation were found for both joint couplings. Consequently, where possible, coordination analysis should be undertaken on an individual basis, with regards to an athlete's specific constraints.

CHAPTER EIGHT

Summary of Findings, Practical Implications, and Future Research

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8.1. Summary of findings

8.1.1. Assessment of start and turn performance.

Chapter Four sought to identify if relationships existed between final race times and commonly used metrics to assess start and turn performance in freestyle, backstroke, and butterfly. As the focus of this thesis is UDK, events included were freestyle, backstroke, and butterfly, up to 200 m races. Strong correlations were found between final race time and start time for all men's backstroke events, and men's 50 m freestyle. However, no strong correlations were found for any women's events for start time. For turn out times, only one significant correlation was found for men's events, in 200 m freestyle. However, strong significant relationships were found between turn out time and final race time for women's 100 m backstroke, 100 m freestyle, and 200 m butterfly. Discrepancies between these results and those of previous studies were suggested to be due to differences in sample size and heterogeneity, particularly as previous authors often included several rounds of competition, e.g., semi-finals and finals (Arellano *et al*., 1994; Cossor and Mason, 2001).

Chapter Four also compared how start and turn times, and clean swim speeds, differed between the top-performing GB athletes and medallists from the rest of the world. Relative to clean swimming speeds, GB male swimmers had slower start and turn times than non-GB swimmers in all events investigated. This was most prominent in 100 m butterfly. Female GB swimmers had quicker start times than non-GB swimmers in 50 m backstroke, 50 m butterfly, 200 m backstroke, and 200 m freestyle, with slower than or equal to non-GB swimmers' start times in other events. Further, for turn-out times in 100 m events, female GB swimmers were faster to 15 m than non-GB swimmers for 100 m butterfly, yet slower in the other two events. For 200 m events, GB females had faster turn-out times than non-GB swimmers for backstroke, yet slower times than non-GB swimmers for butterfly and freestyle. In assessing how turn-out times changed over the course of 200 m races, a general trend was found for both GB and non-GB athletes to have the longest turn-out time for their third turn when assessing group means. However, differences were found between strokes, with a larger percentage of swimmers having the shortest turn-out time on their first turn within 200 m backstroke, followed by butterfly, and then freestyle. These findings highlight the discrepancies between start and turn performance of GB and non-GB athletes.

8.1.2. Determining intra-cyclic speed in UDK

Chapter Five assessed the agreement between speed measures derived from a custom-built velocity-meter (SpeedReel) and an established criterion method of measurement (centre of mass speed calculated from 3D video analysis) during UDK. A secondary comparison was undertaken between the SpeedReel and the speed of the mid-point of the hips, also calculated from 3D video analysis. Limits of agreement were deemed to be unacceptable for both comparisons, as the limits were larger than the smallest worthwhile change. The SpeedReel was found to underestimate mean speed compared with centre of mass speed and mid-hip speed. The SpeedReel also recorded higher maximum kick cycle speeds and lower minimum kick cycle speeds, compared with the centre of mass speed for all participants. For the comparison with mid-hip speed, the SpeedReel recorded higher maximum kick cycle speeds for five of the 13 participants, and lower minimum kick cycle speeds for all participants. Intra-cyclic velocity variation was also found to be higher for SpeedReel than the centre of mass and mid-hip speeds. It is therefore not possible to use the SpeedReel and 3D video analysis interchangeably to measure instantaneous speed.

8.1.3. Kinematics of Prone and Supine UDK

Chapter Six identified significant relationships between elite UDK performance and numerous kinematic variables. Several of these were common across prone and supine kicking, including kick frequency and hip extension velocity. However, knee flexion velocity correlated only with prone UDK performance, and ankle plantar-flexion velocity and hip flexion velocity correlated only with supine UDK performance. Maximum shoulder flexion/extension angle differed significantly between prone and supine kicking, with greater flexion observed when supine than when prone. This chapter also identified differences in kinematic variables between males and females. Males exhibited significantly greater kick amplitudes, maximum toe speeds in both kick phases, and distance per kick. Males had an earlier time of maximum knee separation and later time of minimum foot separation than females. A kick-by-kick analysis demonstrated that faster kickers compensate for a reduction in kick frequency or amplitude and therefore maintain distance per kick. This meant that horizontal COM speed was better maintained over the underwater phase by the faster kickers.

8.1.4. Coordination patterns during UDK

Chapter Seven provided an assessment of coordination during UDK using temporal analysis, angle-angle plots, and Continuous Relative Phase (CRP). For prone kicking, a temporally sequential pattern was observed for the trunk, thigh, shank, and foot for the males in the knee flexion phase but not in the knee extension phase. A temporally sequential pattern was not observed for the females in either kick phase. For supine kicking, a sequential pattern was observed for both sexes in the knee flexion phase, but not the knee extension phase. The angle-angle plots indicated qualitative differences in the hip/knee coupling, both between the fastest and slowest kickers, and intra-individually between kick cycles of each participant. However, CRP analysis demonstrated no quantitative difference between coordination patterns at the hip and knee, or knee and ankle, between prone and supine UDK. For the comparison between males and females, between-cycle variability was found to differ significantly in the knee extension phase, with female swimmers demonstrating higher variability.

8.2. Practical Implications

The results of this thesis contribute towards the body of knowledge on UDK, and provide novel insight into the technique of elite swimmers over the full underwater phase. Furthermore, this thesis presents new information on the temporal, kinematic, and coordination aspects of prone and supine UDK from an elite cohort of males and females. Consequently, some important practical implications emerged.

The identification of deficiencies in start and turn performance of GB swimmers compared with medallists from the rest of the world present performance implications for the GB team. Start and turn times account for a substantial amount of final race time; improvements in these race skills would result in a concomitant increase in performance. As the largest time contribution to overall start time, a focus on developing performance in the underwater phase could provide considerable reductions in race time. Furthermore, ensuring turn-out times do not increase over the course of a 200 m race could be a valuable asset for GB athletes.

Results of this thesis demonstrated that speed measures from the SpeedReel and 3D video analysis cannot be used interchangeably. The SpeedReel is often used within the high-performance swimming environment, both within the Performance Centres and across the World Class Programme in British Swimming. There are also numerous versions of velocity-meters in use by swimming programmes in other countries. Applications of the device range from technique analysis and assessment of underwater performance, to testing of racing suits, caps, and goggles. The findings of this thesis do not invalidate the use of the SpeedReel entirely, yet cognisance of its limitations is key to using it appropriately. The SpeedReel recorded higher maximum and minimum values within kick cycles than the video-derived speed measures. As such, it is not recommended that the SpeedReel be used to quantify and monitor maximum or minimum instantaneous speed. If the device were being used for this purpose with regards to specific performance questions, erroneous conclusions could be drawn, and potentially imprecise information and recommendations provided to the athlete and coach. However, mean overall speeds across the trial were similar between the methods of measurement; as such, it is proposed that the SpeedReel can be used to measure mean overall speed. In conjunction, kick frequency may also be monitored with the SpeedReel. Overall, the SpeedReel can be a useful tool, in combination with other measurements, with which to analyse performance in a holistic manner.

Kick frequency and hip extension velocity were significantly correlated with UDK performance in both prone and supine kicking. Other variables found to correlate with performance in either kicking orientation were plantar-flexion velocity, knee flexion velocity, and hip flexion velocity. As such, it is suggested that coaches and practitioners aiming to assess and improve swimmers' UDK ability focus on monitoring and developing the angular velocities of the lower limbs. Whilst kick frequencies were similar between sexes, males had greater kick amplitude and distance per kick, possibly due to greater height and/or limb lengths than the females. This indicates the need to make decisions on optimum frequency and amplitude on an individual basis with regards to organismic and task constraints, rather than having one recommended value for all swimmers across all events. The fastest male kicker mostly maintained his horizontal COM speed over the trial, by compensating for a decrease in kick frequency with an increase in distance per kick. Whilst this capacity to adapt various kinematic aspects of technique may be somewhat of a natural ability, coaches and athletes should aim to increase, or at least maintain, distance per kick over the underwater phase in spite of reductions to kick amplitude or frequency. Finally, whilst neither metric demonstrated a significant linear correlation with UDK performance, there was a general trend for the faster kickers to have smaller shoulder flexion/extension angles and arm angles of attack. It is therefore recommended that athletes ensure their arms are aligned with the torso, and that their arms and torso are then aligned with the direction of travel.

CRP analysis of the hip and knee, and knee and ankle, revealed no difference in intra-limb coupling between prone and supine UDK. Consequently, the skill may be coached in the same way regardless of kicking orientation. However, the large inter- and intra-individual variability in coordination patterns indicate that there are different movement solutions to this task. These may arise due to particular constraints, whether specific to the athlete and their morphology, or due to the discrepancy between the maximal effort required for the study and their 'normal' technique specific to their main race event and distance. Consequently, it is recommended that the interpretation of coordination analysis within UDK ought to be tailored to the individual athlete.

8.3. Limitations

The findings of this thesis have to be considered in light of some limitations. Due to the Covid-19 pandemic, it was necessary to change some aspects of the project. For example, the original intention was to conduct multiple 3D analysis testing sessions for each athlete so as to obtain longitudinal data and perform intra-individual comparisons. The collection of three to four sessions of data would have facilitated analysis of changes in performance over a specified time period. This, unfortunately, became impossible due to the Covid-related restrictions.

Though all participants were of national or international standard, the range of events in which they competed was quite large, meaning few stroke 'specialists' were included. This sample bias was a natural consequence of availability of athletes on the World Class Programme, however it is important to consider that different results may have been obtained with some of the newer athletes that have since joined the Programme. On a similar note, this thesis found a significant relationship between

UDK performance and kick frequency. However, it is important to note that the fastest kickers in the cohort favour a higher frequency and smaller amplitude technique. Different results may have been found with a different sample of athletes who favoured a higher kick amplitude technique.

A potential limitation within the protocol used for data collection is that depth and distance underwater were not controlled. This was an attempt to maximise ecological validity, as it was important to obtain a representation of what the athletes would do in a race situation; the instruction was to perform their ‘normal’ underwater phase, including breakout. However, differences in trajectory or distance travelled underwater could have had an unquantified effect on the results. It perhaps would have been prudent to obtain additional trials instructing the participants to achieve and maintain a specified depth. Additionally, participants were asked to perform UDK at maximum effort, so as to obtain high velocities from every athlete, instead of varying between athletes who compete in different event distances. For example, the underwater phase of a 50 m sprinter is likely to be tactically different than that of a 200 m swimmer. However, a 200 m swimmer’s race-specific underwater phase may involve dissimilar technique than when performing it at maximal effort. As such, the experimental protocol used may have introduced an unintended task constraint on the swimmers’ technique. It may have been beneficial to have collected additional trials instructing the participants to perform the underwater phase at race pace.

8.4. Future Research Directions

Whilst the chapters in this thesis provide insight into the technique of elite swimmers, the studies were observational in nature. This was an unavoidable requirement of collecting data with athletes from the World Class Programme and having to schedule testing sessions within the periodisation of different Performance Centre coaches, alongside the Covid-related restrictions outlined above. However, future research could investigate the effect of specific interventions on improving UDK within elite swimmers. It may then be possible to ascertain best coaching and support staff practices required to improve UDK technique. This information can then be disseminated to coaches and staff working with younger and developing swimmers, thereby contributing to the knowledge base to coach the acquisition and improvement of this important race skill from a younger age.

The assessment of coordination patterns of the lower limb joint couplings during UDK was a novel aspect of this thesis, and added information to the existing body of knowledge. Future work could look at the differences in coordination patterns under different conditions, such as imposed changes to speed, kick frequency, or amplitude. Additionally, a system for measuring and monitoring coordination changes within the daily training environment would be beneficial. The acquisition and analysis of three-dimensional data, whilst ideal, is not logistically possible within this environment on a regular basis. As such, future work regarding accessible assessment of coordination could be very impactful.

A clear continuation of research from this thesis is to undertake an assessment of muscle activity during UDK. Whilst coordination patterns were ostensibly similar between prone and supine kicking, there were some differences in kinematics; additionally, UDK performance does appear to differ between males and females, and large between-subject and within-subject variation was observed. As such, an investigation into the activation patterns of the muscles involved in UDK may help elucidate differences in technique.

All trials within this thesis were completed following a push-off from the wall. Whilst this is representative of performance during a turn, some kinematic and coordination aspects of UDK technique may differ during the start of the race following a dive entry. Future studies could examine the differences in these factors between starts and turns, for different event distances.

Finally, this thesis aimed to identify critical biomechanical factors contributing to elite UDK performance. However, this skill is not performed in isolation, and the context of its role within the overall race should be considered. Future research should incorporate information from other sports science disciplines, to gain a holistic understanding of how best to improve UDK technique. This could include anthropometric measures such as limb lengths, which may help explain the differences found in UDK performance between sexes, or the physiological impact of increasing kick count and underwater distance following a turn.

8.5. Overall Conclusion

This thesis demonstrated that there are certain key characteristics of elite UDK, including a high angular velocity at the hip, knee, and ankle, and an ability to maintain distance per kick over the underwater phase. It is also evident that, whilst some participants in this cohort demonstrated differences in kinematics between prone and supine kicking, coordination patterns between the hip, knee, and ankle do not differ significantly between kicking orientations. However, it is clear that differences do exist in the kinematics and performance of males compared with females. As such, the coaching of this skill need not differ based upon kicking orientation. However, interventions for improvements in performance should, ultimately, be tailored to each individual swimmer within a multi-disciplinary framework.

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APPENDICES

APPENDIX 1

A1.1 Example of method to calculate percentage change metric.

A scatter plot was generated for each participant in which each metric, in this example kick amplitude, was plotted for every kick cycle (figure A1.1).

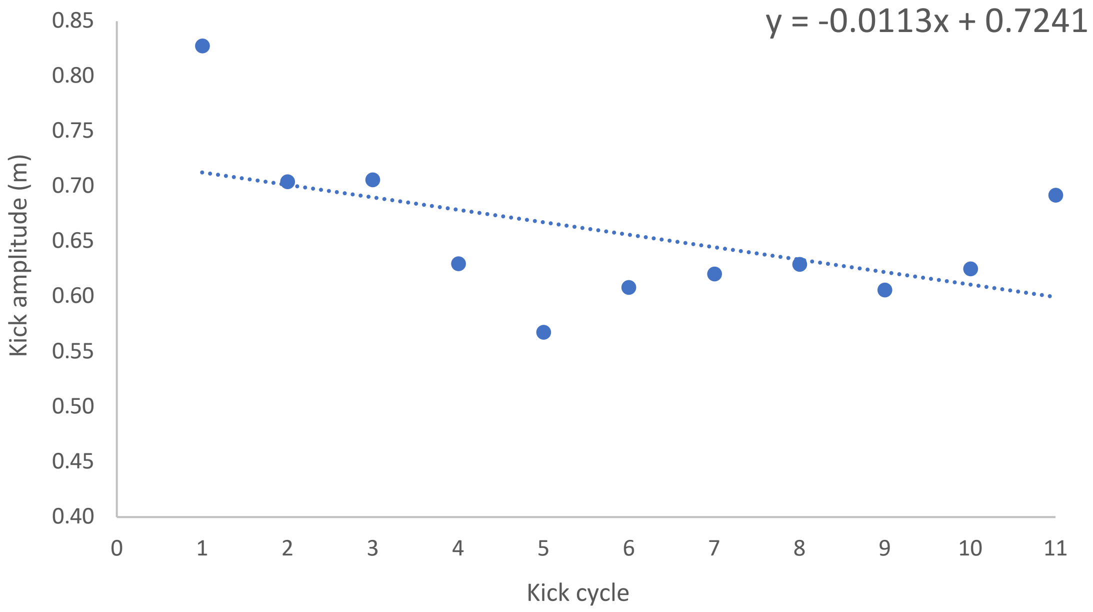

Figure A1.1. Example of scatter plot of kick amplitude for each kick cycle for one participant.

The line of best fit was added, and the slope of this line represented the change in kick amplitude per kick cycle, in this case, -0.0113 m. To find the total change over the trial, this number was multiplied by the number of kicks within the trial:

Total change = -0.113 * 11 = -0.01243

Subsequently, this total change value was divided by the original kick amplitude from the first kick cycle, and multiplied by 100 to generate the percentage change metric.

$$\%\ \text{change} = \left(\frac{-0.01243}{0.82791}\right) \text{x}\ 100$$

This provided the percentage change metric for one participant in either prone or supine UDK. This process was completed for both kicking orientations, for every participant.

A1.2. Example of knee and foot separation

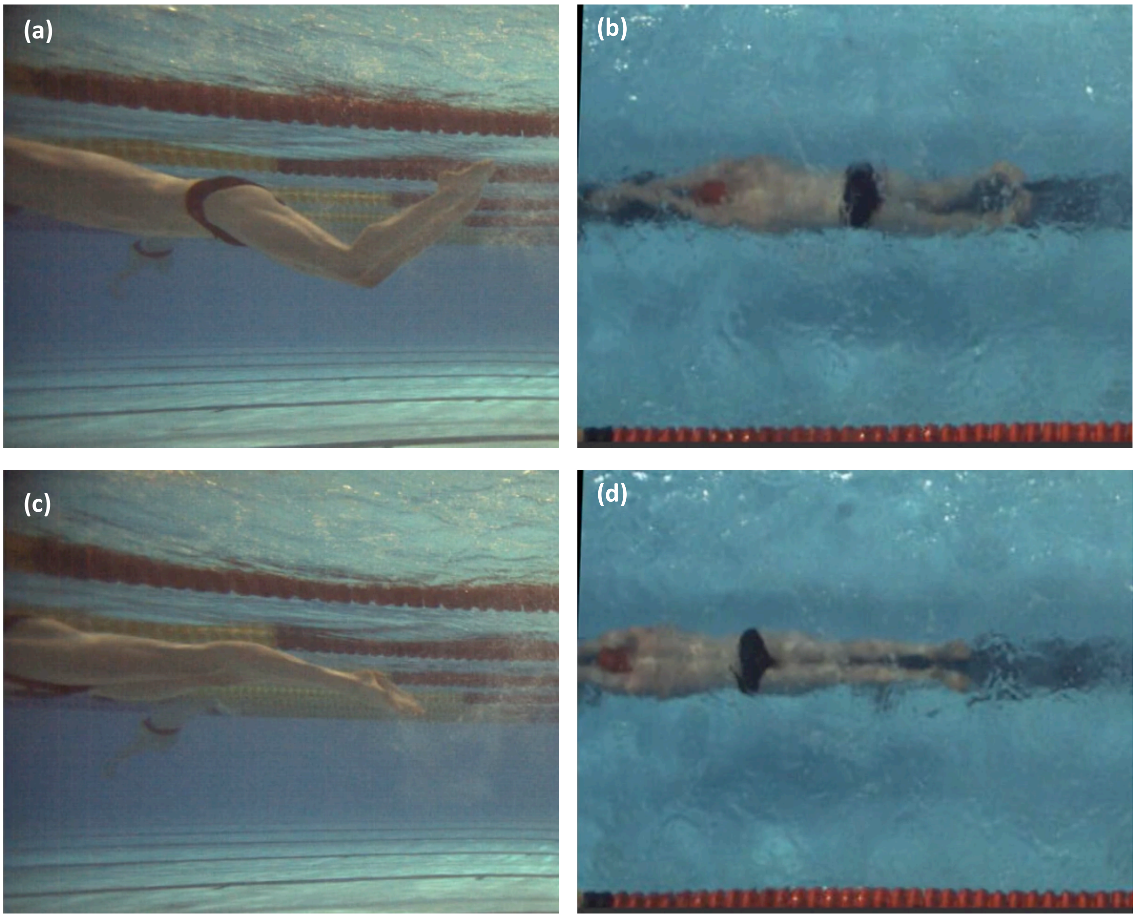

Figure A1.2. Examples of positions of the shank and feet at different points of the kick cycle during UDK. (a) and (b) represent the moment the toes are closest together from the sagittal and coronal view respectively; (c) and (d) represent the same for the moments the toes are furthest apart.

APPENDIX TWO

Participant Information Sheet

Manchester
Metropolitan
University

Participant Information Sheet

BRITISH
SWIMMING

The Critical Physical and Technical Factors Affecting Intra-cyclic Speed Fluctuations in the Underwater Phase of Starts and Turns.

Invitation paragraph

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

What is the purpose of the study?

The purpose of this study is to further inform how we collect underwater phase data, identify the important aspects of the underwater phase that are needed for elite performance, and to identify areas of largest development for individual swimmers to improve performance.

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

You have been invited to take part in this research as you are an elite swimmer from the National Performance Centres, a highly trained swimmer from a club, or a University swimmer.

Do I have to take part?

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

What will I have to do?

Upon arrival, I will prepare you for video capture by placing markers on key sites on your body; for example, your hips, knees, and ankles. During the data collection sessions, you will be required to complete six trials of underwater fly kick, up to 20 m. You will be asked to perform two dives and four push-off trials; essentially, I would like you to do everything you would normally do after leaving the start block or pushing off the wall following a turn. I will take video footage of you swimming using eight underwater cameras that will be placed in the water on tripods; the SpeedReel will also be attached to you, to measure your speed as you swim.

What are the possible disadvantages and risks of taking part?

A full risk assessment has been carried out as part of the University's ethical requirements, and all risks will be managed and minimised.

The possible risks of taking part in this study include the risk of musculoskeletal injuries when completing the whole or part of the underwater phase. However, this risk will be reduced by completing a full warm up before completing any task for this study. Additionally, there is a small chance of discomfort if the line from the SpeedReel gets caught around your leg or foot, but care will be taken on the placement of the line to reduce the likelihood of this. Further, all camera equipment will be stable and at a sufficient distance away from you.

Additional risk assessments have been carried out concerning the COVID-19 pandemic. Researchers and assistants will be wearing full personal protective equipment (PPE) (i.e., type II R masks, apron, and gloves) whenever the need arises to break social distance, e.g., when placing markers on or attaching the SpeedReel to you. We will also require you to wear a face covering during these situations. I have arranged staggered arrival times for all participants to ensure social distance; further, all touch points and equipment will be sanitised between participants.

What are the possible benefits of taking part?

I cannot promise the study will help you specifically however it will help to increase our understanding and knowledge of the underwater fly kick. Consequently, this may increase the understanding of how to improve technique within this skill, and therefore reduce race times.

What if there is a problem?

If you have a concern about any aspect of this study, you may speak to the researchers who will do their best to answer your questions:

Victoria Jones –

If you remain unhappy and wish to complain formally, you can speak to the supervisors of the project:

Dr. Carl Payton –

Mr Oliver Logan –

or the Research & Knowledge Exchange Governance Officer at Manchester Metropolitan University:

Kerri Tomkinson –

Will my taking part in the study be kept confidential?

Procedures for handling, processing, storage and destruction of data will be in accordance with the General Data Protection Regulations. All information and data collected throughout this research will be kept anonymous and be given a participant identifier, known only to the researcher and supervisory team. Any information about you which leaves the National Centres or University will have your name and address removed so that you cannot be recognised. The data and a master list identifying the research codes will be stored on password-protected computers, accessible only to the researchers and supervisory team. In the case that the data needs transferring to another computer or a copy made for a supervisor, the data will also be kept on an encrypted hard drive. The researcher and supervisory team will be the only authorised individuals to view the data unless consent has been given by the participant. Once the research has been completed, the data will be kept on file for 5 years and then destroyed.

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

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

What will happen to the results of the research study?

The results of the research will be used within the researchers' doctoral theses, and possibly published within articles in appropriate scientific journals. Regarding any publications or reports, you will remain anonymous throughout. Following your participation in this study, the video footage will be made available to you and your coaches if you wish.

Who is organising or sponsoring the research?

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

Further information and contact details:

If you have any questions or queries I will be happy to answer them. If I cannot help you, you can speak to Dr. Carl Payton or Mr Oliver Logan. If you have any questions about your rights as a participant or feel you have been placed at risk you can contact Dr. Carl Payton or Mr Oliver Logan.

Consent form

CONSENT FORM

Title of Project: **The Critical Physical and Technical Factors Affecting Intra-cyclic Speed Fluctuations in the Underwater Phase of Starts and Turns.**

Name of Researcher: **Victoria Jones**

Please initial all boxes

1. I confirm that I have read and understand the information sheet dated 13/12/2020 for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason, without my medical care or legal rights being affected. ☐

3. I understand that relevant sections of my data collected during the study may be looked at by individuals from Manchester Metropolitan University or from British Swimming where it is relevant to my taking part in this research. I give permission for these individuals to have access to my records. ☐

4. I agree to be filmed/recorded, which will be used as part of the research project. ☐

5. I agree to take part in the above study. ☐

____________________	____________________	____________________
Name of Participant	Date	Signature
____________________	____________________	____________________

Ethics approval form

Name of Person taking consent.	Date	Signature
19/07/2018		

Project Title: Biomechanical determinants of underwater dolphin kick.

EthOS Reference Number: 0351

Ethical Opinion

Dear Victoria Mary Jones,

The above application was reviewed by the MMU Cheshire Research Ethics and Governance Committee and, on the
19/07/2018, was given a favourable ethical opinion. The approval is in place for four years following the

proposed in your application.

Conditions of favourable ethical opinion

Application Documents

Document Type	File Name	Date	Version
Consent Form	Consent-Form	23/02/2018	1
Project Proposal	Proposal	15/03/2018	1
Information Sheet	Participant Information Sheet	19/06/2018	3
Additional Documentation	Risk Assessments	25/06/2018	1

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

Adherence to Manchester Metropolitan University's Policies and procedures

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

Amendments

If you wish to make a change to this approved application, you will be required to submit an amendment. Please visit the Manchester Metropolitan University Research Ethics and Governance webpages or contact your Faculty research officer for advice around how to do this.

We wish you every success with your project.

Cheshire Research Ethics and Governance Committee