Effects of 50m and 400m Race Paces on Three-Dimensional Kinematics and Linear Kinetics of Sprint and Distance Front Crawl Swimmers

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Many authors have proposed that sprint and distance front crawl swimmers differ in their stroke characteristics, however little three-dimensional quantitative data is provided to support these assumptions. It is currently unknown whether sprint and distance swimmers exhibit distinct stroke characteristics when swimming at the same pace. There were two main purposes of this study: 1) to determine whether there are distinct kinematic and kinetic differences between sprint and distance front crawl swimmers, and 2) to investigate whether stroke characteristics of front crawl swimmers, in terms of kinematic and kinetic variables change with swimming speed.

Fifteen male national/international front crawl swimmers (17.87 ± 2.33yrs; 73.87 ± 8.72kg; 183.02 ± 6.84cm) volunteered to participate in this study. This sample was composed of seven sprint (SG) and eight distance (DG) swimmers. Each testing session required swimmers to perform four 25m sprints and one 400m max effort (front crawl), with no pacing strategy, in a randomised order. Each trial was performed through a $6.75m^3$ calibrated space and recorded by six gen-locked JVC KY32 CCD cameras (4 below and 2 above water) sampling at a frequency of 50 fields per second. All trials were processed using 'APAS' software to obtain 3D coordinate data. Anthropometric measures were quantified using the elliptical zone method. Both data sets were entered into a bespoke MATLAB program which output: average swim velocity (V_{av}), stroke length (SL), stroke frequency (SF), stroke index (SI), vertical and lateral displacement for each segment, shoulder and hip roll angle, and elbow joint angle variables (1st back, shoulder x, end back, hand exit and recovery elbow angle). Stroke phase (entry, pull, push and recovery) durations (%) were quantified at instants corresponding to percentiles of the stroke cycle. Centre of mass position data were obtained from the digitised 3D data using a 14 segment rigid link body model in conjunction with the body segment parameter data obtained by the elliptical zone method. Component whole body velocity (V_{COMHor}), acceleration (acc_{COM}) and net force ($force_{COM}$) were derived from the centre of mass position data. Variables were statistically analysed in SPSS v.14.0, using a General Linear Model, repeated measures analysis of variance.

The results indicated that the groups differed ($p<0.05$) with respect to the duration of the pull phase, the occurrence of max left and right shoulder roll and the temporal sequencing of the shoulders and hips rolling at both sprint and distance pace. Other variables approached significance between the groups, particularly when distance swimming, such as the duration of the push phase ($p=0.082$), the V_{av} ($p=0.071$) and average V_{COMHor} ($p=0.071$). The stroke kinematic variables that changed between paces ($p<0.05$) were the duration of the entry, pull, push, hand exit and recovery phases; the elbow angle at the end back position and the push phase range; total shoulder and hip roll; the sum average vertical displacement of the foot; the time to max vertical and lateral displacement of the finger; the time at max right elbow extension; the average V_{COMHor}, Min V_{COMHor} and Max V_{COMHor}. The stroke kinetic variables that changed between paces ($p<0.05$) were the Min acc_{COM}, Max acc_{COM}, range of acc_{COM}, min $force_{COM}$ and max $force_{COM}$. Other variables approached significance between the paces such as the entry elbow angle ($p=0.084$), the max right elbow extension ($p=0.056$), the finger lateral range ($p=0.067$) and the time to max acc_{COM} ($p=0.079$).

The SG displayed shorter durations of the pull and push phases than the DG for both paces, which was linked to the faster horizontal velocity and/or vertical acceleration of the hand. The sequencing order of the shoulders and hips changed between groups and paces, which was speculated to be controlled by the magnitude of the leg-kick. The main changes between paces were the greater magnitude of elbow angle at both the end back position and the push phase range, which contributed to the adjustment of kinetic variables. SL, SF, SI, V_{av} and the duration of the all the stroke phases changed between sprint and distance pace in order to meet the physiological requirements of the race distance. The prolonged duration of the entry phase, when distance swimming, resulted in a delayed attainment of the catch position and maximum stroke depth. Moreover, the magnitude of shoulder and hip roll increased at distance compared to sprint pace, which in turn influenced the magnitude of average vertical and range of lateral displacement of the finger between paces.

In conclusion, contrary to the literature, SG and DG differed only with respect to the duration of the pull and push stroke phases and the sequencing order of the shoulders and hips. All swimmers adjust the majority of kinematic and kinetic variables depending on the swim pace in order to optimise performance for that race distance.

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Thesis submitted for the degree of Doctor of Philosophy to The University of Edinburgh.

I hereby declare that this thesis is my own work, that it has not been submitted for any other academic award, or part thereof, at this or any other educational institute.

Student:____________________ Date: ________________

Supervisor:_________________ Date: ________________

I would like to take this opportunity to acknowledge many people who have supported me, both academically and socially, along the journey of producing this thesis. In recognition of their contribution, I share this mile-stone with them!

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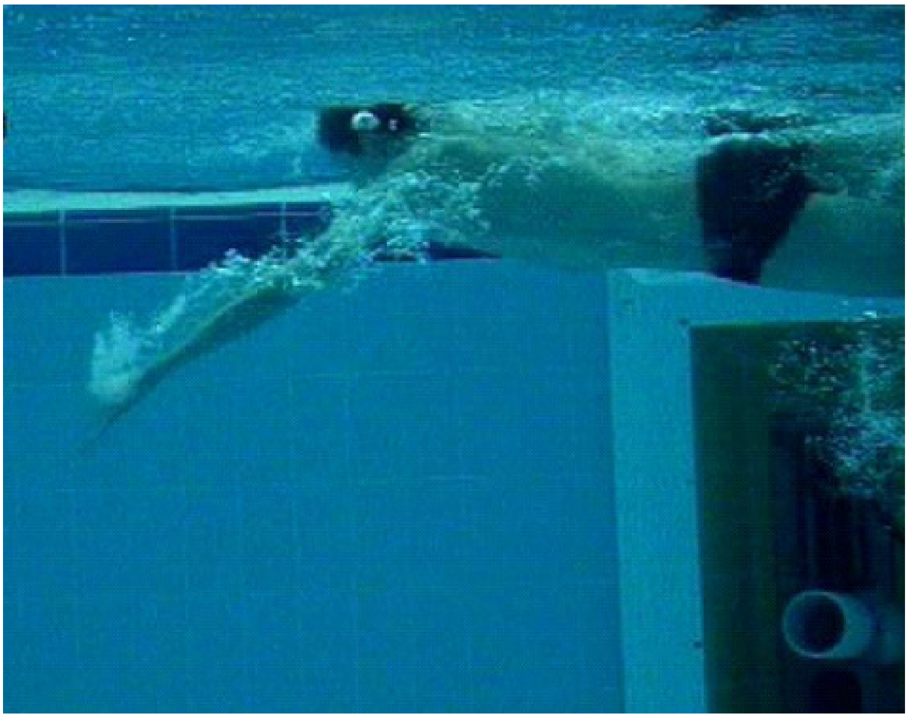
SG	Sprint swimmers/group
DG	Distance swimmers/group
3D	Three-dimensional
2D	Two-dimensional
FINA	Federation Internationale De Natation
COM	Centre of mass
ROM	Range of motion
SC	Stroke cycle
%SC	Percentage of the stroke cycle
SD	Standard deviation
N	Number
Max	Maximum
Min	Minimum
AV	Average
IdC	Index of coordination
BSP	Body segment parameters
MRI	Magnetic resonance imagining
CT	Computed tomography
eZone	Elliptical zone method
DLT	Direct linear transformation
APAS	Ariel Performance Analysis System
SPSS	Statistical Package for Social Sciences
CFD	Computational fluid dynamics
SV	Swimmers speed
V_{av}	Average swim velocity
SF	Stroke frequency
SL	Stroke length
SI	Stroke index
V_{COMhor}	Horizontal velocity of the COM
acc_{COM}	Acceleration of the COM
$force_{COM}$	Net force of the COM

Chapter One: Introduction



Race distances in competitive freestyle swimming tend to be categorised as either ‘sprint’ or ‘distance’ events. The 50m and 100m races are classified as sprint events whilst the 200m, 400m, 800m and 1500m are classified as distance events. Swimmers are inclined to specialise in a particular event to suit their innate and conditioned physiological characteristics (McArdle et al., 1996; Maglischo, 2003). Whilst the genetic predisposition of an individual has been recognised as having a direct link to a swimmer’s performance, other factors such as training, stroke mechanics, coordination, pulling strength and racing ability can overcome one’s genetic ‘disadvantage’ for a particular event (Hohmann et al., 1998; Maglischo, 2003).

Coaches design training programs for sprint and distance swimmers, which include a wide range of intensities, to strategically direct the swimmer towards their peak performance in their chosen event, and to develop physiological aspects regarded as deficient (Lydersen, 1999; Johnson and Gadboy, 1999; Maglischo, 2003). However, the possible impact of this accepted practice on the swimmers’ stroke mechanics has not been considered adequately. Bearing in mind the principle of specificity with regard to training, this is an important consideration. Many authors have speculated that sprint and distance swimmers utilise distinct stroke characteristics in order to achieve maximal performance for their specific event (Colwin, 1969; Costill et al., 1992; Ito and Okuno, 2002; Cappaert, 1998). However, it remains unclear whether these groups vary in terms of kinematic and kinetic characteristics and/or whether these characteristics are influenced by the swim velocity.

Researchers have reported that swimmers adjust the magnitudes of stroke frequency (SF) and stroke length (SL) in relation to swim velocity (Craig and Pendergast, 1979; Pai et al., 1984; Keskinen and Komi, 1993; Pelayo et al., 1996; Cappaert, 1998). However, it is unknown whether both sprint and distance swimmers change SF and SL in a similar manner between swim speeds.

Due to the fact that the arms contribute more to propulsion than the legs in freestyle swimming (Adrian et al., 1966; Counsilman, 1973; Di Prampero et al., 1974; Holmér, 1979; Watkins and Gordon, 1983; Deschodt et al., 1999), the arm trajectory has been assessed to identify stroke patterns which may be associated with optimal performance (Rushall et al., 1994; Deschodt et al., 1996a, 1996b). There is considerable speculation that sprinters utilise a deeper stroke pattern than distance swimmers. Cappaert (1998) reported quantitative data that supported this perception (sprint swimmers: 1.6m, distance swimmers: 1.0m), however the magnitudes of these values are large in comparison to those obtained in similar studies. Distance swimmers have been characterised by a longer SL than sprint swimmers (Okuno et al., 2002; Maglischo, 2003).

Although the lateral component of the stroke pattern is regarded as essential (Maglischo, 1989; Rushall et al., 1994; Deschodt et al., 1996a; Deschodt et al., 1996b), there is disagreement as to which group, if any, produce greater magnitudes. Based on the above indications and the mass of speculation in the literature, it is presumptuous to suggest that the stroke pattern, incorporating lateral, vertical and horizontal displacements, differs between sprint and distance swimmers. It is possible that sprint and distance swimmers utilise similar stroke patterns at specific paces but differ between paces due to the difference in physiological demands. The stroke pattern characteristics reported in the extant literature are unclear in relation to the effects of swim distance specialisation and the pace adopted for sprint and distance events. While some authors have expressed opinions regarding differences with respect to the arm/hand pathways during a stroke cycle (SC- begins and ends with the hand entry of the same arm) between sprint and distance swimmers, it is apparent that more research is required using three-dimensional methods to investigate these differences and the effect of swimming pace as the distance of the event changes.

It has been suggested that the arm trajectory during underwater swimming is related to the magnitude of body roll (Lui et al., 1993; Hay et al., 1993; Payton and Mullineaux, 1996). In fact, Lui et al. (1993) established that the medio-lateral motions of the hand result from the swimmer’s rolling actions of the trunk and not the hand/arm movements relative to the swimmer’s internal reference frame. The magnitude of body roll has been reported to differ between sprint and distance swimmers (Cappaert, 1998) and to be influenced by swim speed (Castro et al., 2002; Yanai, 2003). Specifically, body roll has been found to decrease as swimming speed increases (Castro et al., 2002; Yanai et al., 2003) and that distance swimmers utilise a greater body roll motion than sprinters. However, body roll research has been limited in the past due to the methods of quantifying the angles of this parameter.

Consequently the accuracy of previous data is questionable. Thus there is a need for further investigation of body roll using three-dimensional analysis methods.

The magnitude of the elbow angle has been associated with the arm pathway, force production and limb velocity of the hand, which all contribute to forward propulsion (Deschodt et al., 1996a; Cappaert, 1998; Haffner and Cappaert, 1998; Maglischo, 2003). It has been proposed that sprinters utilise a greater elbow angle than distance swimmers (Wilke, 1992; Cappaert, 1998). Alternatively Voronstov and Rumyantsev (2000) suggested that as the swim velocity increases, so too does the elbow angle, but did not provide quantitative data to substantiate these claims. It is therefore unclear whether the magnitude of the elbow angle is dependent on the swim velocity or influenced by the distance specialisation of the swimmers. Thus, there is a need to examine elbow angle throughout the SC with regard to sprint vs. distance pace and swimmer specialisation.

Sprint swimmers have been characterised by a greater knee range of motion (ROM) during the kick than distance swimmers and this has been proposed as advantageous to propulsion (Cappaert, 1998). It is assumed that, as a consequence of the increased knee ROM, the foot ROM for sprint swimmers would also be greater in sprinting than in distance swimming. But this remains to be established. Further, although swim velocity is known to influence the kicking rhythm (Colwin, 1969; Costill et al., 1992; Maglischo, 2003) the displacement of the kicking motion has not been investigated.

Front crawl swimmers display either a 'one-peak' or 'two-peak' COM velocity pattern (Maglischo et al., 1988; Maglischo, 2003). It has been suggested that the particular style a swimmer adopts is influenced by the body type, hand pattern, body roll and kicking rhythm (Maglischo, 2003). All of these have been found to differ between sprint and distance swimmers. To date, the influence of distance specialisation on COM velocity profile has not been investigated.

Several studies have indicated that regardless of swim velocity, maximum COM acceleration occurs during the last phase of the underwater SC (Maglischo et al., 1989; Rouard et al., 1996; Cappaert, 1998; Maglischo, 2003). This finding suggests that despite variations in the stroke patterns and whether one is a sprint or distance swimmer, critical kinetic elements are core to the stroke. Based on the knowledge that sprinting requires faster and stronger arm movements than distance swimming, it may be that the magnitude of the COM accelerations will differ between the two groups even when swimming at the same pace. Yet kinetic parameters have not been extensively reported in the literature, especially with respect to the influence of distance specialisation and pace. This is due to the methods employed to calculate kinetic parameters which are often viewed as sub-standard in terms of accuracy (Schleihauf et al., 1983, Pai and Hay, 1988; Schleihauf et al., 1988; Berger et al., 1995; Berger et al., 1999; Monteil et al., 1996; Rouard et al., 1996; Lauder et al., 2001; Barbosa et al., 2002). For this study, the elliptical zone method, which provides accurate anthropometric data from which the dynamic COM position is determined, enables accurate derivation of the kinetic parameters. This will assist in establishing the relationships between the stroke kinematics and propulsion.

Many factors are related to swim velocity and success in swimming. The literature has indicated that some of these parameters show variations in relation to sprint and distance swimming. Despite this knowledge, one has difficulty in confidently recognising the differences between these two groups. It is apparent that further research is required to establish the kinematic and kinetic characteristics of freestyle swimming. It is also of interest to investigate whether differences that may occur across speeds are related to speed per se or the specialism of the swimmers, that is, sprint or distance.

It is important to extend this area of research to identify kinematic and kinetic characteristics of both sprint and distance swimming. Such knowledge is necessary to help coaches direct a sprint or distance swimmer to an ideal pattern which is most effective for their particular event. Of great interest is to investigate if either group adjusts their stroke pattern when swimming at a non-preferred swim velocity, as may be the case during training.

1.1. Purpose of the Study

1. To determine whether there are distinct kinematic and kinetic differences between sprint and distance swimmers
2. To investigate whether stroke patterns, in terms of kinematic and kinetic variables, change with swimming speed for sprint and distance swimmers.

1.2. Aim of the Study

The aim of this study is to carry out a biomechanical investigation, which will compare sprint and distance swimmers at a similar pace (sprint and distance) in order to highlight whether sprint and distance swimmers are technically different from each other. Another important aim of this research thesis is to examine whether swimmers adjust their stroke characteristics across swim paces in order to optimise performance. Researching the aforementioned aims will provide coaches and swimmers with useful information with regards to training swimmers who specialise in a particular race event and whether training at various swim velocities would affect the swimmers technique.

1.3. Objectives of the Study

1. Investigate whether the basic stroke parameters differ with respect to sprint or distance swimmers.
2. Examine the vertical and lateral hand displacement by sprint and distance swimmers at both paces to ascertain any differences in stroke pattern.
3. Investigate the elbow angle magnitude and range throughout the stroke cycle to understand whether it changes dependent on pace or swim specialisation.
4. Examine the shoulder and hip roll magnitude independently to obtain a better understanding of body roll at differing paces.
5. Examine the magnitude of foot ROM to obtain a better understanding of the kicking action depending on pace and swim specialism.
6. Investigate if swim groups favour a one or two peak COM velocity curve.
7. Examine the COM acceleration and net force curves in order to obtain a better understanding of the swimming kinetics.

Chapter Two: Literature Review

In order to conduct this study effectively, one must first have a thorough knowledge and understanding of the research area. This is achieved by evaluating and critiquing the pertinent literature relevant to this thesis. In the subsequent sections, aspects related to swim performance, and in particular, related to sprint and distance swimming, are presented.

2.1. Swimming Velocity

Many researchers have formulated ‘swimming models’ in order to identify and present the key deterministic factors related to a swimmer’s performance (Nigg, 1983; Grimston and Hay, 1986; Hay, 1993). Hay (1993) highlights that the prime objective in competitive swimming is to complete the race distance (in accordance to FINA rules) in the least time possible. The time it takes the swimmer is determined by the event distance, and the average speed of the swimmer over that distance (Grimston and Hay, 1986; Hay, 1993). It is assumed that the average speed over longer distances is less, due to the energy constraints to complete that distance. Common to all swimming models are the key factors relating to a swimmer’s speed, over a given distance. These are the product of the stroke length (SL)- *the distance covered during each SC*, and the stroke frequency (SF)- *the number of strokes taken in a given time*. SF is often expressed as the number of stroke cycles swimmers take each minute (cycles/min). Due to the robust relationship between these two parameters and the swimmer’s speed (SV), the SL and SF of a swimmer have been studied extensively and are discussed subsequently.

2.1.1. Stroke Length and Stroke Frequency

Researchers have linked SL and SF with anthropometric characteristics (Grimston and Hay, 1986; Kennedy et al., 1990; dos Santos, 1998), gender (Letzelter and Freitag, 1983; Pelayo et al., 1996; Delaplace et al., 2001) skill level (Chollet et al., 1997; Cardelli et al., 1999), breathing and non-breathing conditions (Castro and Guimares, 2006), and competition analysis (Mason, 1999; Mason and Cossor, 2000; Vorontsov and Rumyantsev, 2000). From these studies it is highlighted that:

- SL and SF have a negative relationship.
- SL is the single most important predictor of swim performance and skill.

- At a similar SF, the main discriminating factor in performance between males and females is SL.
- Females tend to increase SF as a way of maintaining velocity despite smaller SLs than males.
- SL is related to the height of the swimmer, arm span, arm length, leg frontal area, hand and foot cross sectional area, which help explain male superiority with regard to this measure.
- Elite swimmers tend to be taller than sub-elite swimmers, and hence have a longer SL.
- For non skilled swimmers, SF permits faster swimming.
- Skilled swimmers maintain these two parameters consistently between laps.
- SF increases under non-breathing conditions independent of swim pace.
- SF may be linked to arm coordination changes

SL and SF variables have also been investigated in relation to the race distance (Craig and Pendergast, 1979; Keskinen and Komi, 1993; Arellano et al., 1994; Pelayo et al., 1996; Nomura and Shimoyama, 2002; Maglischo, 2003), and report:

- It is the *combination* of SL and SF which are related to successful swimming performance and are varied on an individual basis.
- For both males and females, increasing velocity in short distance events (50, 100 and 200m) is to increase SF.
- SL progressively increases from 50-200m race distances and decreases from 200-800/1500m.

Moreover, it is recognised that the greater SF values when sprinting increases the energy expenditure of a muscle. That is, when the speed of the pulling arm is doubled, the energy expenditure is increased eight times (Counsilman, 1973). Therefore, whilst a faster SF may increase propulsion, it also disproportionately increases the energy expenditure and oxygen consumption. This finding helps explain why sprint swimming is unsustainable for long periods of time.

Table 2.1 presents some numerical results from the above studies. To enhance the meaningfulness of these data with the current investigation, only studies that analysed skilled male swimmers who swam at sprint and distance paces are included. It is evident that the shorter the distance, the higher the average SV, concomitant with a reduced SL and higher SF in relation to distance swimming.

Study	*Swim Velocity ($m \cdot s^{-1}$)*	*Stroke Length (m)*	*Stroke Frequency ($strokes \cdot min^{-1}$)*
Kennedy et al 1990			
- 100m Pace	No Data	2.07 ± 0.23	52.8 ± 0.23
Pelayo et al 1996			
- 50m Pace	2.11 ± 0.05	2.21 ± 0.18	57.61 ± 4.67
-100m Pace	1.94 ± 0.04	2.28 ± 0.19	51.37 ± 4.82
-400m Pace	1.66 ± 0.03	2.24 ± 0.18	44.59 ± 3.34
Seifert et al 2004			
- Max Pace	1.93 ± 0.10	2.16 ± 0.12	53.7 ± 3.6
-400m pace	1.61 ± 0.06	2.66 ± 0.27	36.6 ± 3.6
Seifert et al 2007a			
-100m pace	2.11 ± 0.61	2.13 ± 0.20	51.6 ± 0.05

Table 2.1: Swim velocity, stroke length and stroke frequency data presented from previous research studies.

Table 2.2 shows the SL and SF measures of the first three medal winners from the men’s 100m freestyle final at the 1998 World Championships. Alexander Popov came first by utilising the longest SL of all the medal winners combined with the lowest stroke frequency. General observation of these elite swimmers highlights the importance of the SL to successful performance.

Swimmer	*Stroke Length (m)*	*Stroke Frequency ($strokes \cdot min^{-1}$)*
Alexander Popov	2.49	48.8
Michael Klim	2.31	51.2
Lars Frolander	2.16	54.3

Table 2.2: Stroke length and stroke frequency data for the first three swimmers in the men’s 50m freestyle final, World Championships, 1998. Data taken from Goldsmith, 1999.

2.1.1.1. Limitations with SV, SL & SF Studies

The primary concern with the present literature is with regard to the calculation of these variables. In short, the SV has been calculated in many studies as the time taken to complete either the entire race distance or a specified distance (Kennedy et al., 1990; Keskinen and Komi, 1993; Pelayo et al., 1997; Chollet et al., 1997; Arellano et al., 1994; dos Santos, 1998; Cardelli et al., 1999; Okuno et al., 2002; Seifert et al., 2004a; Seifert et al., 2005; Seifert et al., 2007a; Seifert et al., 2007b; Girold et al., 2007). SL and SF have been quantified commonly as the number of strokes performed to complete the distance and time taken, or with the use of specialised stopwatches (Kennedy et al., 1990; Keskinen and Komi, 1993; Chollet et at., 1997; Pelayo et al., 1997; Cardelli et al., 1999; Seifert et al., 2004a; Minghelli and Castro, 2006; Seifert et al., 2007a; Seifert et al., 2007b). Although these methods are recognised in the field and serve their purpose to provide feedback with quantitative measurements of SV, SL and SF, the accuracy and validity are questionable. This is further supported by Chollet and Pelayo (1999) who reported that different procedures used to assess SL yield discrepant results. Consequently, comparisons between previous research projects will be performed cautiously. Moreover, it has not been established whether sprint and distance swimmers, as a group, display a different SL/SF relationship, or whether this relationship is primarily affected by the swim velocity.

2.1.2. Stroke Index

A relatively recent parameter reported in the literature is the ‘stroke index’ and is presented due to its association with the above parameters. Stroke index (SI) is determined as the product of SL and SV. Researchers regard this parameter as a measure of successful performance (Costill et al., 1985; Sanchez and Arellano, 2004) and as a practical tool to assess swimming ability (Pelayo et al., 1997). Male swimmers have a greater SI than female swimmers in all events (Sanchez and Arellano, 2004). This is not surprising based on the previous literature that male swimmers typically display higher magnitudes of SL and SV than female swimmers. Sanchez and Arellano (2004) also found that front crawl swimming has the greatest SI value followed by backcrawl, butterfly and breaststroke and that it decreases progressively with increases in race distance. These findings are expected based on the knowledge that front crawl swimming permits the greatest SV of all strokes, and generally as a race progresses, both SV and SL decrease.

Although evidence supports the assumption that SI is greater in sprint than distance events, the magnitude of this variable with regard to sprint and distance swimmers, swimming at their preferred and non-preferred race distances, has not been investigated. In particular, it will be interesting to examine how swimmers change this variable between paces.

2.2. Components of Swim Performance

Movement of any kind in an aquatic medium is greatly affected by resistance due to water being 100 times more dense than air. Consequently, the swimmer experiences a retarding force known as resistance/drag when moving through the water, which acts in the opposite direction of travel (Costill et al., 1992). There are many sources of drag in swimming; namely form, frictional and wave drag. Form drag takes into account the space and shape of the swimmer's body to the oncoming flow. Frictional drag is the layer of friction between the swimmer's skin and the stream of water molecules in contact with the skin, and how these molecules behave. Wave drag is regarded as the turbulence created at the water surface which acts to inhibit forward motion. The magnitude of wave drag increases with higher swim velocities (Hay, 1993; Maglischo, 2003), with a wall of water (bow wave) created in front of the swimmer which results in an increase in resistive drag. Studies have revealed that bow waves can exert a retarding effect to forward motion by a factor of eight when swimming velocity is doubled (Maglischo, 2003). Vorontsov and Rumyantsev (2000) calculated that the wave making drag force is proportional to the cube of the swimming velocity, whereas they calculated the form drag to increase with the square of the velocity. This means that the relative contribution of wave-making resistance to the total hydrodynamic resistance becomes important at near maximal swimming velocities and may be a factor limiting increase in swimming speeds. The most recognised method to reduce the influence of wave drag is to swim at a slower pace. However, if one wishes to win a race, this option is not a desirable one. Consequently, swimmers seek to minimise wave drag through effective technique.

Nevertheless, successful performance is determined by the propulsive forces a swimmer generates during the SC whilst minimising the resistive forces acting on the body. In other words, a swimmer will accelerate in the forward direction only when propulsive forces, generated by the body segments, are greater than the opposing resistive forces and will slow down when the resistive forces are greater than the propulsive forces (Voronstov and Rumyantsev, 2000). Propulsion is the force that drives the swimmer forward through the water in reaction to the movements of the swimmer's limbs (Counsilman, 1973; Hay, 1993; Voronstov and Rumyantsev, 2000). The literature unequivocally highlights that the arms contribute more to propulsion than the legs in front crawl (Adrian et al., 1966; Counsilman, 1973; Di Prampero et al., 1974; Bucher, 1975; Holmér, 1975; Secher and Oddershede, 1975; Miyashita, 1975; Smith, 1978; Holmér, 1979; Watkins and Gordan, 1983; Hollander et al., 1988; Engesvik, 1992; Toussaint, 1992; Riberio et al., 1994; Deschodt et al., 1999; Maglischo, 2003). Several studies have explained this finding due to the legs requiring significantly more energy than the arms to yield equivalent propulsion (Adrian et al., 1966; Holmér, 1974; Di Prampero et al., 1974; Holmér, 1975; Ohkuwa and Itoh, 1993; Riberio et al., 1994; Maglischo, 2003). Smith (1978) noted that this was due to the larger mass of active muscle in the legs. Long distance swimmers naturally decrease the contribution of the leg kick as a means of conserving energy, delaying the onset of fatigue, acting as a stabiliser to the body and thus improving the swimmer's horizontal body position to reduce resistive drag and the energy requirement to sustain a given speed (Counsilman, 1973; Holmér, 1975; Watkins and Gordon, 1983; Engesvik, 1992; Maglischo, 2003). Alternatively, because sprinters have no need to conserve energy, kicking at a high intensity is advised to increase propulsion (Maglischo, 1988, cited in Wilke 1992; Maglischo, 2003).

2.3. Kinematic Aspects of Front Crawl Swimming

Seifert et al. (2004a) stated that SV, SF and SL components are not sufficient to examine swim performance as they do not indicate the associated changes in technique. Rather it is certain kinematic variables which provide a more comprehensive understanding of the influential aspects of swim speed (Seifert et al., 2004a). The kinematic variables associated with swim speed will be discussed in the following sections.

2.3.1. Arm Displacement

It is widely acknowledged that the arm trajectory consists of a combination of horizontal, vertical and lateral motions in order to achieve forward propulsion of the body (Counsilman, 1973; Schleihauf, 1982; Schleihauf et al., 1983; Maglischo, 1989;

Costill et al., 1992; Deschodt et al., 1996a; Deschodt et al., 1999; Payton et al., 1999; Maglischo, 2003). There are indications in the literature that swimmers automatically adjust their pulling pattern according to swim speed (Colwin, 1977; Cappaert, 1998; Ito and Okuko, 2002). At high velocities swimmers use a straighter elbow and thus a deeper pulling action than when swimming at moderate velocities for longer distances, whereby a more prominent lateral sweeping action that permits the hand to cross the body's centre line is used (Colwin, 1977). The benefit of these adjustments has not been specified in the literature.

The component of the hand displacement in line with the intended swimming direction is regarded as playing a major role in generating propulsion (Maglischo 1989; Rushall et al., 1994; Maglischo 2003). This is explained by Newton's 3rd law *'For every action there will be an equal and opposite reaction'*. Adapted for swimming purposes, it was reasoned that pushing the water back created a counterforce of equal magnitude that propelled the swimmer forward. This propulsive force (F) was determined by the mass (m) of water and the acceleration (a) of the water in accordance with Newton's 2nd law equation: F=ma. As well as the amount of water (mass) accelerated, the time over which it is, is considered important due to the change in motion (momentum) of a body being the product of force and time. Indeed Deschodt et al. (1996a) (n=44 100m competitive freestyle swimmers during French national championships) established a link with the backward displacement of the wrist, elbow and shoulder segments to increasing the swim velocity (measured as the hip velocity). It has been found that skilled swimmers (front crawl) typically demonstrate a backward displacement of the hand within the range 0.4-0.5m, whilst less skilled swimmers have hand displacements of 0.6-0.7m (Voronstov and Rumyantsev, 2000). Deschodt et al. (1996a) revealed a 0.8m horizontal displacement of the wrist. It was also noted that the wrist has on average a 0.2m greater horizontal displacement than the elbow. Although sprint and distance swimmers have not specifically been investigated with regard to the magnitude of arm horizontal displacement, it has otherwise been reported that distance swimmers display a longer (horizontal) SL than sprint swimmers (Okuno et al., 2002; Maglischo, 2003). However, it is assumed that perhaps this is most likely due to the race distance event, rather than group differences per se. The magnitudes of arm displacements from previous studies are presented in Table 2.3.

Skilled swimmers also display large vertical motions of the arm segments (Schleihauf, 1982; Costill et al., 1992; Deschodt et al., 1996a; Deschodt et al., 1996b). These movements have been related to the forward velocity of the swimmer (Rushall et al., 1994; Deschodt et al., 1996a). Costill et al. (1992) recommended a maximum hand depth of 0.4-0.6m for all swimmers. Maglischo (2003) added that the hands should travel 0.5-0.7m vertically from the surface, in order to place them in a backward facing position at the 'catch'. Deschodt et al., 1996a found that the wrist reaches a maximum depth of 0.78m whilst swimming a 100m race. Payton et al. (1999) (n= 6, competitive male swimmers, swimming at 200m pace) reported the hand segment to reach a maximum vertical displacement of 0.79 ± 0.04m. Cappaert (1998) analysed sprint (below 200m) and distance (above 200m) Olympic and world championships male swimmers and reported that sprint swimmers utilised a deeper pulling pattern than the distance group (1.6m vs. 1.0m). However, due to the greater values reported in the latter study (in relation to other studies), one should interpret this finding with caution. Nevertheless a greater vertical trajectory of the hand path is believed to be advantageous as a method of increasing the frontal area of the propulsive segments and allowing such segments to exert an increased force, both in an upwards and backwards motion (Schleihauf et al., 1983). Moreover, Cappaert (1998) speculated that the vertical displacement of the arm is related to the elbow angle. It was suggested that a straighter arm pull would result in a deeper pull pattern, yet this connection has not been established in the literature, and will be investigated in this study.

As the arm segments travel backwards researchers have revealed that the wrist and elbow illustrate a sinusoidal, or curvilinear, pathway (Counsilman, 1973; Rushall et al., 1994; Deschodt et al., 1996a). It was reasoned that once swimmers started a mass of water moving, they could no longer elicit the same reaction force from it without substantially increasing their hand speed. This is due to the water and body segment moving in the same direction, i.e. the water is moving with the hand, the hand speed relative to the water is reduced resulting in a reduction in the propulsive force. It was proposed that swimmers stroked laterally, to continuously find 'still' water that allowed the swimmer to achieve a greater reaction force than when a swimmer pulled directly backwards (Counsilman, 1973; Sanders and Stewart, 1992, Voronstov and Rumyantsev, 2000). The literature reveals that the arm lateral motions have been regarded as non-propulsive, yet the importance of this action is believed as an essential component of the underwater stroke trajectory (Maglischo, 1989; Rushall et al., 1994; Deschodt et al., 1996a; Deschodt et al., 1996b). Researchers have proposed that lateral actions are beneficial in terms of stroking efficiency by enhancing the propulsion aspects of the SC and increasing the SL (Counsilman, 1977; Costill et al., 1992; Maglischo, 2003). Deschodt et al. (1996a) did not provide quantitative data in relation to the arm lateral displacement, but observed that the elbow follows a flatter lateral pathway than the wrist during the underwater cycle. The latter study also suggested that individual's present very different arm lateral deviations during the underwater SC. Payton et al. (1999) showed that swimmers stroked with a maximum lateral displacement of 0.27 ± 0.07m when swimming at 200m pace. Although sprint and distance swimmers have not been compared with regard to the magnitude of arm lateral displacement, it has been speculated that distance swimmers tend to include more lateral motions for an energy efficient stroke pattern (Maglischo, 2003). Employing the vortex theory to describe propulsion in swimming, Colwin (2002) explained that at low speeds, swimmers produce a smoother and more rounded stroke pattern than when sprinting, whereby a single impulse of propulsion is produced at the end of the SC. However, no quantitative data has supported these assumptions.

Study	*Horizontal Displacement (m)*	*Vertical Displacement (m)*	*Lateral Displacement (m)*
Payton et al. 1999	-	0.79 ± 0.04	0.27 ± 0.07
Payton and Lauder, 1995	-	-	0.34 ± 0.07
Schleihauf et al. 1988	-	-	0.37 ± 0.08
Deschodt et al. 1996a	0.8	0.78	-
Girold et al. 2007	-	0.85 ± 0.06	

Table 2.3: Finger displacement data from previous studies.

In conclusion, many authors have expressed *opinions* regarding differences with respect to the arm/hand pathways during a SC between sprint and distance swimmers but empirical data is currently lacking. In order to test these ideas and perceptions it is necessary to conduct research in which movement is quantified in three dimensions. Moreover, it is important to assess whether stroke patterns differ with respect to the swim distance specialisation as well as the swim pace.

2.3.2. Body Roll

The displacement and trajectories of the arm have also been related to the magnitude of body roll (Lui et al., 1993; Hay et al., 1993; Payton and Mullineaux, 1996). Body roll is often defined as the rotation of the entire body about its longitudinal axis (Colwin, 1969; Colwin; 1977; Colwin, 2003). The integration of this element into the front crawl stroke has many functions which are considered important for successful front crawl swimming:

- Keeps the body in lateral alignment and decreases resistance (Colwin, 1977; Costill et al., 1992; Castro el al., 2002; Maglischo, 2003).
- Places upper limbs in effective positions in which to generate propulsion (Colwin, 1969; Haffner and Cappaert, 1998; Castro et al., 2002; Maglischo, 2003).
- Brings the large trunk muscles into play, providing a greater capacity for force production (Colwin, 1969; Colwin, 1977).
- Permits the underwater pull to continue directly backward and for a longer period of time (Colwin, 1969; Leonard, 1992; Maglischo, 2003).
- Associated with easing the recovery of the stroke (Colwin, 1969; Colwin, 1977; Leonard, 1992; Maglischo, 2003).
- Facilitation of turning the head to breathe is also improved with incorporating a body roll into the stroke (Colwin, 1977; Payton et al., 1999).

More recently it has been suggested that body roll influences the underwater pathway of the armstroke. This relationship was first investigated by simulation studies. Hay et al. (1993) devised a two-segment rigid body model (the trunk and right arm) which were joined at the shoulder as a hinge joint. Before each testing condition, the rigid arm segment was assigned a pre-selected elbow flexion angle and the hand motion was made in a plane through the shoulder parallel to the sagittal plane of the rotating trunk (Hay et al., 1993). It was evident from this study that the medial trajectory of the hand towards the trunk was entirely due to body roll alone. The authors noted that in order to achieve this handpath, required less body roll (19-34°) than what is usually observed by competitive swimmers. Hay et al. (1993) further reported that when one rolls more than that necessary to produce the desired medial handpath, the swimmer should press the arm laterally away from the midline. The researchers concluded that when studying the swimmer's handpath, one should give more consideration to body roll. However, the limitation of this study was due to the fact that the underwater pull phase is rarely, if ever, executed with a constant elbow angle. Secondly, constraining the hand to move only in the plane through the right shoulder and normal to the shoulder axis is invalid as swimmers are noted to constantly move their hands laterally relative to this plane (Payton et al., 1997).

Acknowledging these limitations Payton et al. (1997) made appropriate modifications to establish a three-segment rigid body model. The arm was represented as a two-segment model which was hinged at the elbow to enable elbow flexion and extension. The arm was linked to a rigid trunk with a shoulder joint capable of extension and shoulder abduction/adduction. Movement of the hand beyond the plane through the shoulders and normal to the shoulder axis was also feasible. Payton et al. (1997) found that body roll influences the mediolateral and vertical pathways of the hand and hence affects the hand speed. It was also noted that when body roll was increased, so too was the squared hand speed in the plane perpendicular to the swimming direction. It was suggested therefore that an increase in body roll has the potential to develop greater lift forces.

One major drawback from the aforementioned simulation studies is that the validity of the models used has not been established. The creditability of any mathematical model of human motion ultimately rests on its validity, which is its ability to accurately represent the essential features of the real-life motion (Hay et al., 1993). Until this is the case, the results obtained from these simulation studies can only be regarded as preliminary.

One of the first experimental studies to investigate the influence of body roll and the handpath in front crawl swimming was conducted by Liu et al. (1993). Ten male collegiate front crawl swimmers were asked to swim three (15m) trials at a long distance pace. Body roll was quantified by strapping a balsa wood fin (mounted on a curved aluminium base) to the swimmer's back. Analysing the motion of the balsa fin was assumed to represent that of the body roll. The body roll angle is defined as the angle between the edge of the fin and the vertical axis (Fig. 2.1). The maximum body roll angle ranged from 51.5-66.0° (mean 60.8 ± 4.4°). The researchers recognised that this angle was greater than what was expected, yet it was acceptable due to the different population and speed requirements of this study. The contribution of body roll to the actual handpath ranged from 41.1% to 73.6%, with a mean value of 52.1%. It was therefore concluded, that on average, body roll and relative motion of shoulder, elbow, or both contributed equally to the medial-lateral motions of the hand- a result which conflicts with Hay et al.'s (1993) prediction that hand motion was determined entirely by body roll.

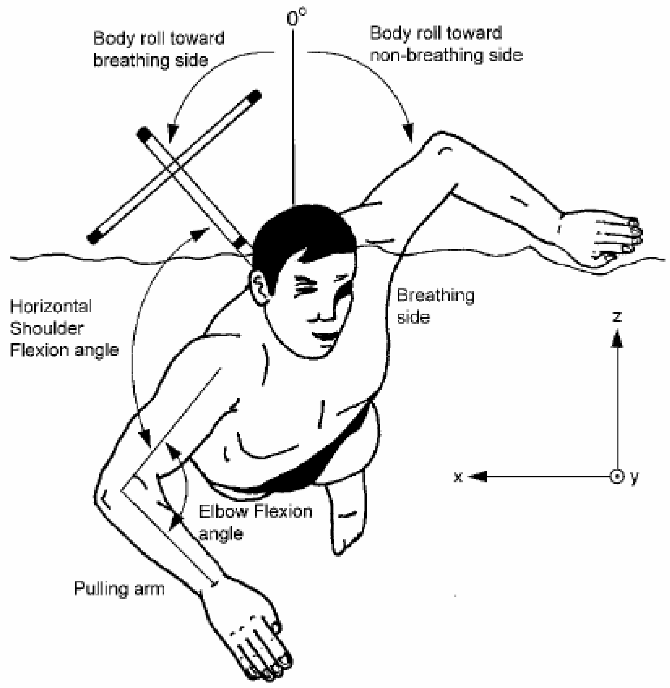


Figure 2.1: Illustration of body roll angle, from Payton et al., 1999.

Liu et al. (1993) further presented that the relative motion of the hand during the pull phase, firstly travelled away from, and then back towards the midline of the trunk. This was exactly the reverse of that predicted by the previous simulation studies. In a subsequent study, Payton et al. (1999) also emphasised that body roll was not responsible for the medial motion of the hand. In fact, body roll was found to oppose medial hand motion, rather than assist it during the insweep.

A further prediction made from the simulation studies was that body roll had the capability of increasing the swimmer's hand speed (Payton et al., 1997), which Payton et al. (1998), in an experimental study intended to determine. Six male experienced swimmers performed several 25m trials at their 100-200m race pace. The balsa fin technique, positioned at the level of the inferior borders of the scapula, was also employed in this study. Three-dimensional coordinates of the hand and shoulder were obtained by manual digitisation. It was reported that body roll reduced hand speed by an average of 1.04 ± 0.28m·s^{-1} during the insweep. The researchers predicted that if the swimmers had maintained the same shoulder and elbow movement patterns, without adding any body roll, their mean hand speeds would have been 46% (± 15%) higher. However, Payton et al. (1998) highlighted that these results should not be construed to mean that one will achieve greater hand speeds by rolling less- as any changes in body roll are likely to be accompanied by compensatory changes at the shoulder and elbow. The researchers suggested that the negative contribution of body roll to hand speed was due to the swimmers rolling back towards the neutral position before, or close to, the start of the insweep. The previous simulation studies assumed that the body rolled away from the neutral position at this phase of the armstroke. It was therefore concluded that body roll opposed the medial motion of the hand rather than facilitating it during the insweep, or alternatively assisted the swimmer's body in rolling back toward the neutral position.

Payton et al. (1999) extended the body roll literature by investigating the trunk and upper extremity kinematics during both preferred side breathing and breath-holding conditions when swimming front crawl. Six male competitive swimmers performed 12 trials (25m) at their 200m race pace. Half of the trials required the subject to breathe to their preferred side, with the other half to hold their breath through the calibrated area. Body roll was quantified using the balsa fin technique. This study revealed, on average, that a swimmer rolled 9° more when breathing (66 ± 5°) compared to breath-holding (57 ± 4°). The researchers proposed that the additional body roll assisted the swimmer in turning their head so the mouth was clear of the water. The study also detailed that front crawl swimmers can perform the breathing action without significantly interfering with the basic stroke parameters. Castro et al. (2002) replaced the balsa fin with a PVC stick to investigate the contribution of body roll when swimming at three different velocities and whilst breathing and non-breathing. Ten male competitive swimmers performed six (25m) trials at a warm-up pace, a 1500m pace and a 50m pace, under breathing and non-breathing conditions. The results indicated that although breathing required a greater body roll angle magnitude than non-breathing, this variable appears to be more influenced by the swim velocity than the breathing condition (Table 2.4). Nevertheless, in this investigation participants were required not to breathe for the length of the calibrated area to avoid any possible effect of stroke kinematics.

Condition	*Trial*	*Velocity ($m \cdot s^{-1}$)*	*Body Roll Angle 'θ' (deg)*
Breathing	1	1.27 ± 0.07	139 ± 5
	2	1.50 ± 0.07	133 ± 9
	3	1.88 ± 0.08	113 ± 12
Non-Breathing	4	1.33 ± 0.11	129 ± 8
	5	1.61 ± 0.08	117 ± 10
	6	1.94 ± 0.07	110 ± 16

Table 2.4: Mean swim velocities and mean body roll angles; n= 10; during two conditions: breathing and non-breathing. Trials 1 & 4= warm up pace. Trials 2 & 5= 1500m pace. Trials 3 & 6= 50m pace. (Adapted from Castro et al, 2002).

Moreover, as seen in Table 2.4 Castro et al. (2002) indicated that the body roll angle tends to decrease as the velocity increases for high level sprint swimmers, which was further supported by Yanai (2003). It was therefore concluded that sprint swimming was characterised by a smaller range of body roll than distance swimming. Because sprint swimmers were involved in Castro et al's (2002) study, it is not known whether distance swimmers would display similar characteristics. In terms of swim groups, Cappaert (1998) revealed that sprinters roll less (average 20.9°) than the distance group (36.9°). It was suggested that due to the rapid nature of sprinting events these swimmers may not need to spend as much time lengthening their stroke during the catch phase to emphasise body roll (Cappaert, 1998). Although Cappaert (1998) reported these differences to occur between swim groups, the swim pace was not considered as a factor, and therefore it remains unclear whether sprint and distance swimmers roll with different magnitudes or whether this is a consequence of the swim velocity. Therefore, further research is warranted to clarify these issues.

The literature has focused on the magnitude of the body roll represented as a motion of the whole trunk. Cappaert et al. (1995) was the first to subdivide body roll into two distinguishable components, namely the shoulder roll and hip roll. Establishing three-dimensional coordinates of the body, both these elements were quantified. Both the magnitude and temporal aspects of the shoulder and hip roll were considered. The participants of this investigation included 12 male, 100m front crawl swimmers, who competed in the 1992 Olympic Games. The main finding was with respect to the symmetry of the total body roll. Elite swimmers displayed a symmetrical body roll, with both shoulders and hips rolling in the same direction, whereas sub-elite swimmers demonstrated an asymmetrical body roll pattern, with the hips rolling in the opposite direction to the shoulders. From these results it was suggested that elite swimmers had a reduced active drag due to a symmetrical body roll; whereas the opposing body roll between the shoulders and hips of the sub-elite group may have increased the active drag by increasing the frontal surface area. Additionally, Colwin (2003) added that better streamlining and a natural flow of water, moving along the body, is enhanced by using the ‘2 part body roll’ in which the shoulders roll first followed by the hips. It is unknown whether a possible ‘relationship’ of the shoulders leading the hips when rolling, is consistent over all speeds or is more obvious in one particular swim group than the other.

A further development in understanding front crawl body roll has been contributed by Yanai. Firstly, Yanai (2001) examined what specifically causes the body to roll in front crawl swimming- whether it was a turning effect due to fluid forces (external torque) or a reaction effect due to the acceleration of the limbs (internal torque) acting on the long-axis through the centre of mass (COM) of the body. Yanai (2001) found that the overall contribution of the external torque was to propel body roll, while the reaction effects of limb accelerations resisted body roll. In a subsequent study Yanai (2004) further elaborated that it was the buoyant force which determined the magnitude of the body roll and that skilled swimmers used the buoyant force as the primary source of generating body roll. Moreover it was revealed that the buoyant force is dependent on the swim velocity, in that faster swimmers used the buoyant force more effectively to generate body roll than slower swimmers (Yanai, 2004). Finally, Yanai (2003) hypothesised that the rolling action of the body could be connected to the kicking action of the legs through a mechanical formula he derived. It was proposed that since the fluid forces generated by the kicking action and the moment of inertia of the body exhibit a three sinusoidal cyclical pattern in a SC may explain why swimmers adopt a six beat kick. However, the magnitude of body roll concomitant with the other kick patterns (2 beat, 4 beat etc) are not discussed with regard to this formula which currently weakens its application.

The aforementioned studies (with the exception of Cappaert, 1998 and Yanai 2001-2004) implemented either the balsa fin or PVC stick technique to quantify the body roll angle. In applying this method, one assumes that body roll is representative of the trunk rolling as a rigid unit. Studies conducted by Cappaert et al. (1995; 1996) have revealed that this is not the case; therefore the validity of these techniques is questionable in terms of accuracy. Further, the positioning of the balsa fin or stick along the trunk may have significant implications since researchers have quite recently documented that the shoulders and hips of select subjects roll in opposition relative to one another (Cappaert et al., 1995; Cappaert et al., 1996; Colwin, 2003). Another limitation of this technique is that the motion of the balsa fin or stick was analysed from one camera view only, typically the front (Lui et al., 1993) or rear view (Payton et al., 1998; Payton et al., 1999). Therefore, this parameter has in the past been assumed to be two-dimensional in nature. Because swimming is a three-dimensional activity, it is unlikely that body roll only occurs in a two-planar motion. This study will create a three-dimensional representation of each swimmer in which the magnitude of the shoulder and hip roll may be calculated independently and with improved accuracy compared to previous methods used in the literature.

In conclusion, this study involves two groups of swimmers, (sprint and distance) who will be required to swim at their specialist and non-specialised race paces. It is recognised, for example, that sprinters have a smaller body roll angle than distance swimmers- yet it is unknown when they swim at a distance pace, if the body roll angle changes to resemble that of a typical distance swimmer, and vice versa. It is also of interest to examine the temporal aspects of this parameter when both swim groups swim at their specialist and opposing race paces.

2.3.3. Elbow Angle

The elbow angle is discussed regularly in the literature primarily due to its influence on the arm trajectory during the underwater phase (Hay et al., 1993). This variable is also believed to have the highest impact on the stroke as it determines the efficiency and power of the applied propulsive force by the arm during the underwater SC (Counsilman, 1973; Colwin, 1977; Cappaert, 1998; Haffner and Cappaert, 1998; Deschodt et al., 1996). Voronstov and Rumyantsev (2000) have identified important functions of swimming with a bent elbow, which are adapted in the following paragraphs:

1. Adjustment of the elbow angle can permit an increase in angular velocity and acceleration of the arm without involving the shoulder. Therefore, less muscle torque is required and the pulling force is more effective.
2. Elbow flexion reduces frontal area of the swimmer and permits the propulsive forces to be applied in the desired (backwards) direction.
3. The ability to apply force is greater when the elbow is partly flexed than fully extended.

With no rationale, the majority of literature highlights that swimmers tend to exhibit a 90° elbow angle throughout the underwater SC (Colwin, 1969; Colwin, 1977; Maglischo et al., 1989; Costill et al., 1992; Maglischo, 2003). There is a paucity of information in the extant literature with regard to whether this angle changes with swim speed or race distance. The recommendation of 90° is based on the assumption that this angle offers maximal motor recruitment to maximise force (Mc Ardle et al., 1996). The following summarises the literature with respect to elbow angle:

- The angle tends to be closer to 100° than 90° (Counsilman, 1973).
- Butterfly and front crawl swimmers demonstrate a maximal elbow angle in the middle section of the underwater pull of 90-120° (Voronstov and Rumyantsev, 2000)
- A straighter arm during the underwater cycle results in a longer pull pattern and slower cycle rate (Cappaert, 1998).
- Female swimmers tend to stroke with smaller elbow angles than males because they are weaker in terms of muscular strength (Counsilman, 1973).

Moreover, based on observations, Wilke (1992) and Cappaert (1998) commented that sprinters tend to have a larger elbow angle (120° and 106.5° respectively) than distance swimmers and also greater than the ‘recommended’ 90°. Voronstov and Rumyantsev (2000) added that the magnitude of elbow angle increases as swim velocity increases. That is, at sprint events, swimmers would display greater elbow extension angles, while in distance event swimmers would tend to stroke with greater flexion angles. However, no quantitative data have been presented to substantiate these claims. It is therefore construed, that a degree of uncertainty and discord is present with regard to the elbow angle literature.

Discrete phases within the SC are often identified in the literature in order to analyse performance characteristics within each phase. However, there is a considerable lack of literature in which both the magnitude of the elbow angle at particular events during the SC and how the elbow angle is influenced throughout the duration of the SC have been reported. Nevertheless, some researchers have recommended that the 90° elbow angle should be maintained throughout (Costill et al., 1992; Maglischo, 2003), whilst others have expressed that it changes continuously (Counsilman, 1973; Vorontsov and Rumyantsev, 2000). Payton et al. (1999) supported the claim that the elbow angle is not constant by highlighting that male competitive swimmers show a 45 ± 14° elbow angle range during the pull phase of the SC. Therefore, concomitant with the fact that little research has explored the elbow angle throughout the SC, it is also a matter of interest whether these variables are influenced by the swimming specialisation or as a consequence of swim velocity. To date neither have been investigated sufficiently.

2.3.4. Timing between the Arms

Swimming is cyclic in nature. Cyclic motion is defined as the motion of the body from one place to another produced by the repetition of a basic sequence (or cycle) of body movements (Hay, 2002). In swimming it is the repeated sequential actions of the arms and legs that aid in the motion of the swimmer. It is imperative that the sequencing of these actions is not interrupted in order to provide continuity and speed to forward motion (Colwin, 1969; Lerda and Cardelli, 2003; Maglischo, 2003). It is also essential that the timings, particularly between the arms, is adaptable so that the physiological and performance objectives are met (Chollet et al., 2000; Millet et al., 2002; Lerda and Cardelli, 2003; Seifert et al., 2004a; Seifert et al., 2004b; Seifert et al., 2007a; Seifert et al., 2007b).

Initially, the timing or coordination between the arms was assessed by visual inspection of video footage combined with qualitative feedback. Costill et al. (1992) and Maglischo (2003) commented that the most important event in the timing between arms is that one arm should enter when the other is midway through its insweep/pull phase. It was also emphasised that following entry the arm should not begin sweeping down until the other has completed its upsweep (Costill et al., 1992; Maglischo, 2003), which permitted the swimmer to obtain a hydrodynamic position in the water whilst applying propulsive force (Costill et al., 1992; Voronstov and Rumyantsev, 2000; Maglischo, 2003). However, the relative timing between the arms has not been explored with regard to either the swim velocity or the swim distance specialisation.

More recently, researchers have investigated the coordination between the arms throughout the SC. Chollet et al. (2000) developed the 'index of coordination' (IdC) as a tool to quantify the relationship between arms when swimming front crawl in a standardised manner. This index is based on quantifying the *lag time* between the start of propulsion by one arm and the end of propulsion by the other. In order to achieve this Chollet et al. (2000) divided the SC into four discrete phases: Entry 'A', Pull 'B', Push 'C' and Recovery 'D' (Figure 2.2). The process of subdividing the SC into distinct phases:

- Establishes criteria for clear identification of phases so that comparative investigations of swimming strokes can be made (Wiegand et al., 1975).
- Is a useful method of quantification- phases exist independent of swim velocity and level of swim performance, resulting in an effective tool for coaches and teachers to assess the development of technique (Wiegand et al., 1975).

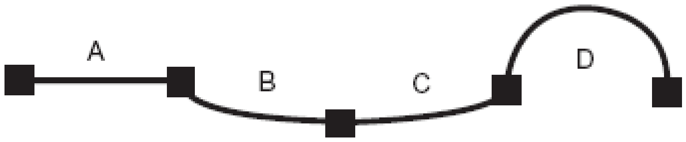


Figure 2.2: Four phases within a stroke cycle. Adapted: Chollet al., 2000

'Lag time 1', was defined as the time between the beginning of propulsion in the first right arm stroke and end of propulsion in the first left arm stroke. 'Lag time 2', was defined as the beginning of propulsion in the second left arm stroke and the end of propulsion in the first right arm stroke. These lag times were then expressed as a percentage of mean duration of a SC resulting in IdC1 and IdC2 respectively. Figure 2.3 shows that the IdC was the mean of these two indices (TL1 +TL2).

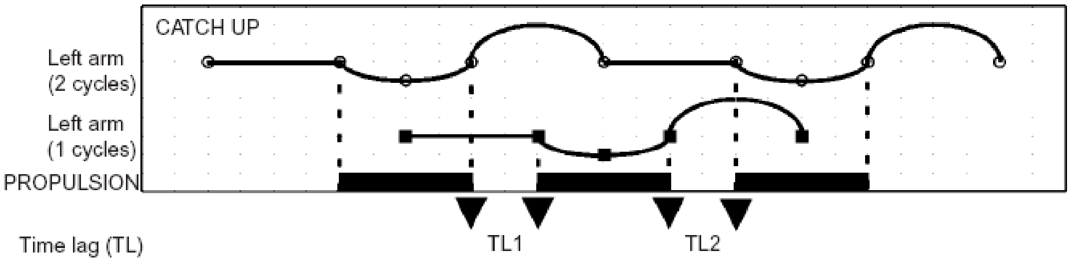


Figure 2.3: Coordination illustration adapted from Seifert et al., 2004a

Using this measure Chollet et al. (2000) identified three modes of front crawl swimming: 'catch up' - lag time between the propulsive phases of two arms (IdC < 0); 'opposition' – describes propulsive actions whereby one arm begins pull while the other is finishing the push (IdC = 0); and 'superposition' – describes an overlap of the propulsive phases (IdC>0). To test this new tool Chollet et al. (2000) examined the relationship between 44 French National division swimmers, swimming at 800m, 100m and 50m pace. It was found that IdC increased with swim velocity. That is, at 800m pace, swimmers displayed a 'catch-up' style, whilst at 100m and 50m pace, 'opposition' style was the most prevalent. The best swimmers displayed a superposition between the arms at 50m pace. In particular, the increase in relative duration of propulsive phases was evident in the pull phase.

Other researchers have adopted this tool to examine front crawl coordination: between elite swimmers and triathletes (Millet et al., 2002), gender adaptation (Seifert et al., 2002; 2004; 2007a; 2007b); effect of swim velocity (Lerda and Cardelli, 2003; Seifert et al., 2004); effects of drafting in elite triathletes (Chollet et al., 2000b), during exhaustive exercise (Alberty et al., 2002), the effect of breathing and skill level (Lerda and Cardelli, 2003; Seifert et al., 2005)

From these studies it has been found that

1. Swimmers and triathletes adapt their stroke pattern from a catch up style to an opposition style when changing from long distance pace to max pace. This resulted in a decrease in entry phase duration and an increase in pull and push phase therefore enhancing longer propulsive forces (Millet et al., 20002; Lerda and Cardelli, 2003; Seifert et al., 2007).
2. Men change from catch-up to opposition spontaneously at a critical velocity and SF corresponding to 100m pace ($1.8m{\cdot}s^{-1}$) and 40strokes/min. Women adopt their pattern progressively (Seifert et al., 2004a; Seifert et al., 2007b).
3. A critical change of coordination occurred at the 100m pace, which was explained by the subject sample being sprint specialists who changed to a preferred pattern at the 100m pace (Seifert et al 2004a).
4. Only the best male performers can adapt a superposition stroke pattern (Lerda and Cardelli, 2003; Seifert et al., 2002; Seifert et al., 2007b).
5. Top performers demonstrate a shorter push phase, resulting in a greater acceleration of the hand during this phase (Lerda and Cardelli, 2003).
6. Skilled and less skilled swimmers illustrate changes in breathing pattern at different velocities (Lerda and Cardelli, 2003).
7. Elite swimmers show no change in arm coordination when breathing. Sub-elite change arm coordination when breathing (Seifert et al., 2005).

Table 2.5 presents quantitative data from previous studies with regard to the duration of each stroke phase and the coordination index. To enhance the meaningfulness of the data, only values in relation to sprint or distance swimming are presented.

	IdC (%)	*Entry (%)*	*Pull (%)*	*Push (%)*	*Recovery (%)*
Chollet et al 2000					
800 Pace	-6.9 ± 7.1	30.3 ± 6.5	21.3 ± 4.2	22.9 ± 2.7	25.5 ± 2.4
100m Pace	2.5 ± 4.4	22.1 ± 3.9	26.7 ± 3.7	26.3 ± 2.7	24.9 ± 2.6
Seifert et al 2004a					
400m Pace	-7.8 ± 4.5	31.8 ± 5.8	22.5 ± 3.5	20.0 ± 2.0	25.8 ± 4.0
50m Pace	1.1 ± 6.0	20.0 ± 6.7	28.7 ± 4.5	22.5 ± 3.1	28.8 ± 2.6
Max Pace	2.6 ± 6.1	18.5 ± 6.3	28.8 ± 5.1	23.6 ± 2.8	29.1 ± 3.6
Millet et al 2002					
Max Pace	2.3 ± 4.8	21.5 ± 3.3	27.0 ± 2.5	26.6 ± 2.9	24.8 ± 2.1
Seifert et al 2007a					
Max Pace	5.4 ± 3.4				

Table 2.5: Presentation of previous research results of Index of Coordination and time spent in each stroke phase, expressed as a percentage of the SC.

From these studies it was also identified that sprinters decreased the entry phase so that they could begin the propulsive phase of the next armstroke almost immediately as the other arm releases pressure. This method is responsible for increasing the energy cost of swimming because it increases the resistance in front compared to stretching the front arm forward in a streamlined manner. Nevertheless, it has the benefit of increasing the turnover rate and results in fast times for short distances. In middle-distance and distance races, swimmers choose to sacrifice speed and conserve energy by delaying the downsweep until the propulsive phase of the stroking arm has been completed (Costill et al., 1992). However, the duration of each stroke phase with respect to sprint and distance swimmers, combined with swim velocity as a condition, has not yet been investigated. This warrants attention to understand whether swim groups emphasise particular stroke phases at the velocity they are accustomed to, or whether they adapt these durations based on the swim velocity.

Moreover, the previous quantification of the stroke phases is based on visual inspection of the SC and is therefore subjective. Seifert et al. (2007a) was more cautious than the other coordination researchers by recognising an error <0.04secs between three independent operators. Nevertheless, the current literature using the IdC tool incorporates a degree of error due to the subjective manner of estimating and quantification of stroke phases. An additional problem with the current method of quantifying coordination is the requirement to measure this variable over a series of three or four strokes (Chollet et al., 2000; Seifert et al., 2004a; Seifert et al., 2007b) to achieve acceptable accuracy.

Finally, although the effect on coordination of swim velocity has been investigated, only sprint swimmers have been included as the sample tested. Indeed Seifert et al. (2004) noticed that the 100m pace was the critical velocity that swimmers changed from a catch up style to a superposition style, by changing the relative durations of the stroke phases. It was reasoned that this abrupt change occurred due to a preferred pattern because they were sprint swimmers. However, no research to date has explored whether a group of distance swimmers would adapt their coordination pattern or stroke phase durations when swimming at various swim velocities and whether there is a noticeable modification of their coordination parameters when swimming at a preferred pace. This study will examine the relative stroke phase durations of both sprint and distance swimmers at their preferred and non-preferred swim velocity.

2.3.5. Leg Action

It is widely accepted that the role of the leg-kick in front crawl swimming to forward propulsion is significantly less than that generated by the arms (Holmér 1975; 1979; 1983; Watkins and Gordon, 1983; Deschodt et al., 1999). As mentioned previously, this is due to the energy demands of the leg muscles (Di Prampero et al., 1974). This 'secondary' role may explain the lack of research with regard to the lower leg limbs in terms of kinematic characteristics. It has been found, in particular relation to longer distance events, that the legs act to stabilise and aid rotation of the trunk when swimming front crawl (Counsilman, 1973; Watkins and Gordon, 1983; Costill et al., 1992; Voronstov and Rumyantsev, 2000; Maglischo, 2003). It is also well known that the kick consists of primarily up and downbeat kicks that incorporate a lateral component. It is the lateral component which is believed to keep the body in good lateral alignment and balanced throughout the SC (Costill et al., 1992; Maglischo, 2003). The majority of the leg kick literature concerns the kicking pattern or rhythm that the swimmers utilise. Front crawl swimmers tend to display a six, four, or two-beat kick (and variations of these) per SC. For example, a six beat kick consists of six complete ascending or descending leg movements within the SC. Persyn et al. (1983)

investigated the kick pattern in relation to anthropometric characteristics of the swimmer. They found that two-beat swimmers tended to have longer legs and because six-beat kickers were those whose legs experienced a greater sinking force, they compensated by utilising a six-beat kick. Perhaps this trend is specifically related to the two swim groups. It has also been reported in the literature that swimmers travelling at higher velocities tend to display a six-beat kick pattern whereas those competing in longer distances tend to favour either a four-beat or two-beat kick pattern, primarily due to the energy demands of the event (Counsilman, 1973; Costill et al., 1992; Maglischo, 2003). However, there is a lack of information with regard to the displacement of the feet during the kicking action and whether this differs across speeds or distance specialisation. With no displacement guidelines, it is impossible to provide confident recommendations to swimmers and coaches as to the extent of kicking range. This knowledge is important in developing the appropriate kicking rhythm and perhaps propulsion generated from the legs. Indeed Cappaert (1998) reported that Olympic and world class sprinters were characterised by a greater knee bend than the distance swimmers indicating an increased range of motion of the foot through the water to generate propulsion. It is therefore suggested that displacement data of the foot would provide a more transparent insight into this assumption and will be investigated in this study.

2.4. Kinetic Aspects of Front Crawl Swimming

Understanding swimming kinetics, allows one to evaluate the propulsive and resistive characteristics of the kinematic aspects, as highlighted above. However, knowledge of the kinetics of swimming is limited. This is primarily due to the inability to accurately calculate kinetic aspects such as accelerations of the COM and net force. These aspects are discussed in sections 2.9.1- 2.9.3.

2.4.1. Net force acting on the whole body obtained from acceleration of the COM.

The net COM force of the body is the total force applied to the water in order to propel forwards. It incorporates the propulsive and resistive forces during the SC. Due to the aquatic environment, it is virtually impossible to measure the body's net force directly. Measuring it indirectly by double differentiation of the COM position data requires knowledge of the COM position, which in turn requires digitising a full body model and using estimates of segments masses and COM locations relative to segment endpoints. Consequently, no studies to date have reported quantitative data for this measure. Additionally, it is unknown whether the net force differs between sprint and distance swimmers, or whether it is influenced by the swim pace.

The combination and interaction of the magnitude of COM net propulsive and resistive forces determines the COM velocity, and acceleration profiles of the swimmer throughout the SC. These components are discussed in the subsequent sections.

2.4.2. COM Velocity

To further establish the propulsive phases, the velocity of the swimmer's COM has been studied extensively. This measurement has become a valuable tool in research, as this indicates when and to what extent phases of the SC are effective in propelling the body forwards (Maglischo et al., 1989; Alves et al., 1994). Therefore, by aligning the swimmer's COM velocity profile with their corresponding actions during the SC, the actions that influence the interplay between propulsive and resistive forces, can be identified. COM velocity profiles have been examined and produced for all four competitive swimming strokes. Accelerations and decelerations throughout the SC are characteristic of all strokes (Nigg, 1983; Maglischo et al., 1989; Mason et al., 1989; Mason et al., 1992; Vilas-Boas, 1992; Cappaert et al., 1996; Colman et al., 1998; Fujishima and Miyashita 1998; Colwin, 2003; Maglischo, 2003; Chollet et al., 2004). An increase in COM velocity, that is, acceleration, indicates that propulsion is greater than resistance, while deceleration indicates that resistance is greater than propulsion (Colman et al., 1998).

Few researchers have investigated the COM velocity profiles of front crawl swimmers (Maglischo et al., 1989; Maglischo, 2003) compared to other strokes (Mason et al., 1989; Colman et al., 1989; Mason et al., 1992; Vilas-Boas, 1992; Sanders, 1996a; Sanders, 1996b; Alves et al., 1998). However, COM velocity profiles have not yet been examined with regard to sprint and distance swimmers nor the change across different swim velocities. The literature does indicate that front crawl swimmers tend to display a ‘one peak’ (Figure 2.4) (one large peak per armstroke) or ‘two peak’ (Figure 2.5) velocity pattern (two distinct peaks during each armstroke, separated by a period of deceleration). Differing styles for the other three competitive strokes include: backcrawl (two vs. three peaks), breaststroke (peak at end of stroke vs. peak earlier in stroke), and butterfly (one vs. two vs. three peaks). Obviously, as the name of each stroke pattern suggests, the particular style that the swimmer uses influences the COM velocity fluctuation throughout the SC.

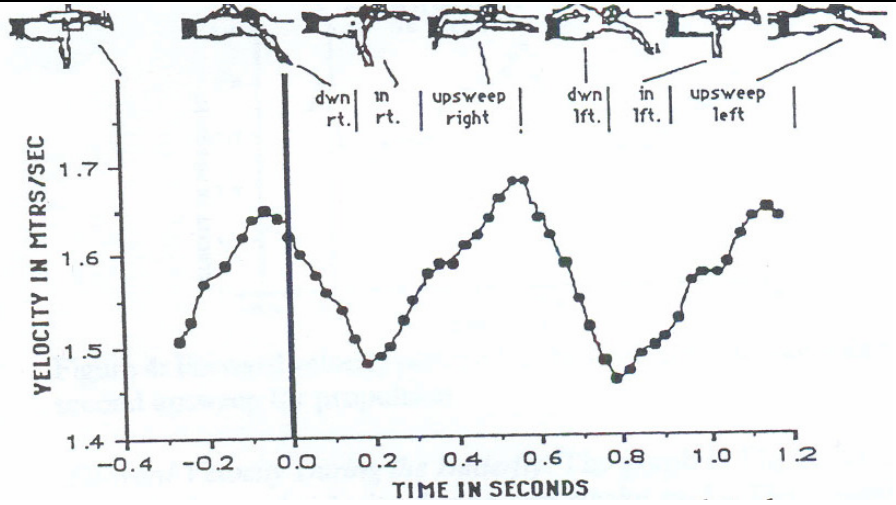


Figure 2.4. One peak velocity profile. Each peak occurs during the upsweep (push) phase of each armstroke: Maglischo, 2003.

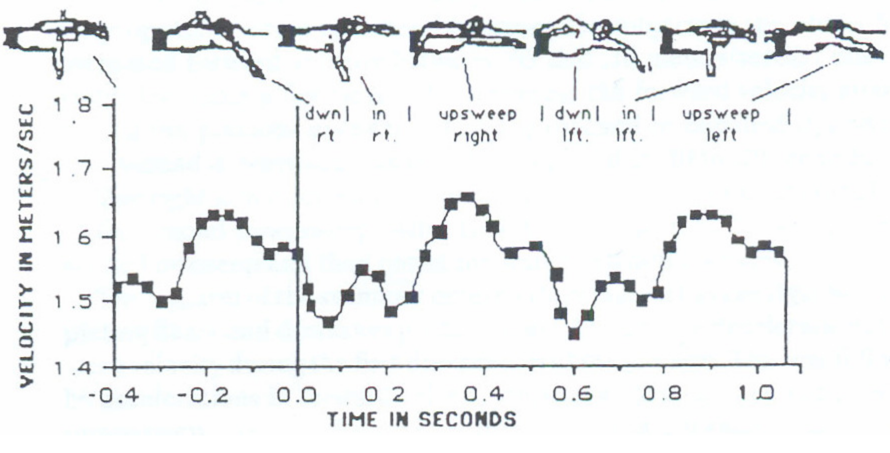


Figure 2.5. Two peak velocity profile. A small peak occurs during the insweep (pull) phase followed by a bigger peak during the upsweep (push) phase for each armstroke: Maglischo, 2003.

Maglischo et al. (1989), digitised 10 world-class swimmers to create 2D data. Using anthropometric data of Dempster (1955), Maglischo et al. (1989) produced a velocity curve of the COM. However, analysis of these curves, like other researchers (Mason et al., 1989; Mason et al., 1992) was completed by qualitative visual inspection. Consequently, due to the subjective analysis of these profiles and the paucity of studies, it is unclear whether a one peak or two peak velocity pattern is more effective in propelling the body. Maglischo (2003) offers the opinion that the two peak pattern is recommended as it has a greater potential to be more effective in terms of achieving a higher velocity per SC over a greater length of time. This assumption is deducted from the following: 1) one can achieve a higher average velocity per armstroke because the propulsive force is applied over a longer time with less muscular effort, 2) potential for a longer distance per stroke due to increased diagonal motion, 3) one segment of water is accelerated, after which another slower segment is accelerated backward; which should result in the two-peak swimmers achieving the same forward velocity as one peak swimmer but with a longer and slower armstroke. Moreover, it has also been speculated a ‘one-peak’ or ‘two-peak’ velocity pattern is dependent on the trajectory of the swimmer’s stroke pattern (Maglischo et al., 1988; Maglischo, 2003). The one-peak velocity pattern is exemplified by an almost directly backward pulling action, whereas the two-peak velocity pattern is believed to contain more diagonal and lateral motions of the arm/hand. Based on Maglischo’s assumption with respect to the stroke pattern characteristics, it is likely that swimmers who display the two-peak velocity pattern may use both greater elbow and body roll angles in addition to larger arm/hand displacements than one-peak velocity swimmers. It has also been suggested that the particular style a swimmer adopts is influenced by factors such as body type, hand pattern and kicking rhythm (Maglischo, 2003) - all of which have been shown to differ between sprint and distance swimmers. Perhaps the style and COM velocity profile of a swimmer is a function of the race distance or swim velocity to which they are accustomed. This has not been considered to date. It may be possible that sprint or distance swimming is characterised by a one or two-peak COM velocity profile. Other variables such as body roll, elbow angle or orientation etc. have not been investigated to date with regard to the COM velocity profile.

2.4.2.1. COM Velocity Fluctuations

A scientifically logical and broadly accepted assumption is that the smaller the range of fluctuation in COM velocity during the SC the less energy is wasted, thereby allowing the swimmer to optimise swim speed (Nigg, 1983; Fujishima and Miyashita, 1998; Voronstov and Rumyantsev, 2000; Kjendlie et al., 2002; Colwin, 2003; Maglischo, 2003; Barbosa et al., 2005). Thus, the magnitude of velocity fluctuations within a SC is an indicator of swimming proficiency (Holmér, 1979; Holmér, 1983; Colwin, 2003). Similar to COM velocity profiles, many studies have investigated the horizontal intracyclic velocity fluctuations of the COM in butterfly (Mason et al., 1992; Sanders et al., 1996b) and breaststroke swimming (Mason et al., 1989; Colman, et al., 1998) but not front crawl swimming. Perhaps this is due to larger velocity fluctuations in these strokes compared to front crawl swimming (Holmér, 1973). Specifically Colman et al. (1998) analysed 28 international male and female breaststroke swimmers, and found that the flat-style swimmers exhibited a 76% range of mean swim velocity, whereas undulating-style swimmers exhibited a 53% range of average swim velocity. These findings indicate that the undulating style is more energy efficient than the flat breaststroke style.

Maglischo (2003) referred to a COM velocity profile of a world class front crawl swimmer whose velocity decreases by 1m/sec during the SC. Maglischo also cited a study by Miyashita (1997) who reported decreases in velocity of 0.5-0.8$m \cdot s^{-1}$ for skilled swimmers. In a comprehensive study conducted by Psycharakis and Sanders (2008) 10 male front crawl swimmers were analysed during a 25m maximum sprint. They reported an average COM velocity of 1.68 ± 0.05 $m \cdot s^{-1}$, an average maximum COM velocity of 1.85 $m \cdot s^{-1}$ which occurred at 32% of the complete SC, and an average minimum velocity of 1.48 $m \cdot s^{-1}$ occurring at 61% of the entire SC. This resulted in a COM fluctuation of 0.37 $m \cdot s^{-1}$. Nevertheless, it is assumed, due to the nature of sprint swimming, that sprinters obtain a greater maximum COM velocity during the SC than distance swimmers. Similarly, it is predicted that distance swimmers aim to conserve energy during a longer race distance and display less COM fluctuations. However, these assumptions have not yet been quantitatively validated in the literature.

It should also be mentioned that the literature indicates that the COM velocity fluctuations are strongly influenced by the stroke pattern of the arms (Schleihauf, 1979; Counsilman, 1981; Barthels, 1982; Schleihauf, 1982; Hollander et al., 1988; Maglischo, 1989; Toussaint and Beek, 1992; Deschodt et al., 1996a; Deschodt et al., 1996b; Rouard et al., 1996; Cappaert, 1998; Haffner and Cappaert, 1998; Ito and Okuno, 2002). Consequently, more knowledge of the COM velocity profile and intra-cyclic motions is warranted with regards to front crawl swimming.

2.4.2.2. Limitations Associated with COM Velocity Studies

The ability to interpret the velocity profiles with confidence depends on the anthropometric data used in the calculation of the COM. It is necessary that precise and accurate segment mass, and location of the COM for each body segment relative to the segment endpoints are used.

Two primary methods are used in the previous literature to calculate the COM velocity of a swimmer. In some studies the motion of the hip has been assumed to be representative of the swimmer's velocity (Mason et al., 1989; Persyn et al., 1990; Mason et al., 1992; Deschodt et al., 1996b; Alves et al., 1998; Barbosa et al., 2002; Buckwitz et al., 2002). In others, the motion of the COM has been determined (Cappaert et al., 1996; Cappaert and VanHeest, 1998; Colman et al., 1998; Barbosa et al., 2005; Psycharakis and Sanders, 2008). Using the hip as a substitute for measuring one's COM is an economic method of calculation compared to calculating the position of the COM following digitisation of a full body model. Some researchers have reported that the method of simply tracking the hip is inaccurate and unreliable (Mason et al., 1989; Persyn et al., 1990; Mason et al., 1992; Colman et al., 1998; Barbosa et al., 2002; Psycharakis and Sanders, 2008). The profiles of the swimmers' hips were found to fluctuate with greater magnitude and were out of phase with the velocity and acceleration profiles of the COM (Mason et al., 1989; Persyn et al., 1990; Mason et al., 1992; Colman et al., 1998; Barbosa et al., 2005; Psycharakis and Sanders, 2008). Figure 2.6 clearly illustrates that the motion of the hip does not accurately reflect the COM motion.

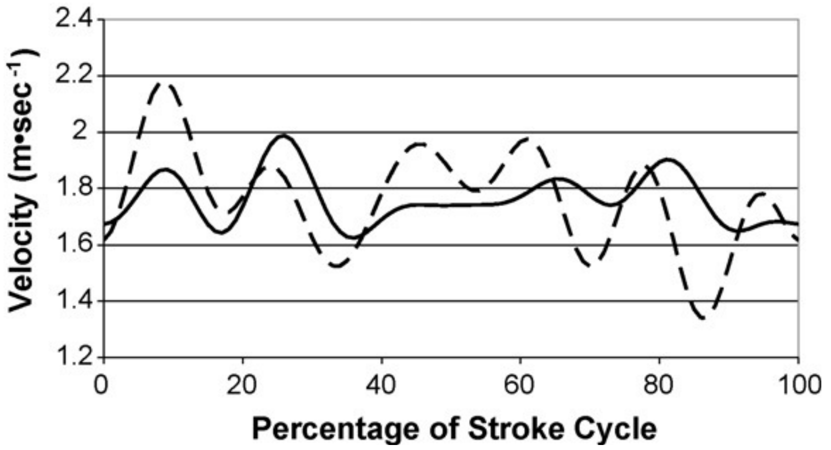


Figure 2.6: Intracycle velocity of the hip (dashed line) and the centre of mass (continuous line) for one swimmer. With permission: Psycharakis and Sanders, 2008.

To estimate the COM accurately many points on the body must be digitised at each instant (video field) using three-dimensional data collection and analysis techniques. This requires digitising synchronised above and below water views of the swimmers and independently scaling and transforming the data to a common three-dimensional frame of reference. Continuous paths of the body parts that move above and below the water surface, for example, the shoulders, elbows, wrists and hands, are then obtained. However, the majority of research studies conducted in this field are of a two-dimensional nature and consequently cannot be used as a true representation of swimming motion as it ignores the rotations of the body or replicate the exact motions of the body when swimming.

In addition to the lack of front crawl COM velocity data reported in the literature, there is a paucity of data comparing sprint and distance swimmers, and changes with change in pace.

As identified in the previous sections, the importance of quantifying the body COM accurately is imperative for velocity measures. In the following section, the most popular methods used in the past are identified and analysed.

2.4.3. Method of Calculating COM

Several sources of body segment parameter data (BSP data - segment masses and segment mass centre locations relative to the segment endpoints), required to calculate the COM, are available. These include data using studies of cadavers, mathematical models, and data from radiation and MRI techniques.

2.4.3.1. Data from Cadavers

Initial attempts to advance the understanding of human physiological and biomechanical functions were through dissection techniques. Dempster (1955) recorded details of the planes of dissection, which consequently resulted in a degree of standardisation of methodologies for subsequent research. On dissecting eight Caucasian male cadavers (52-83yrs; mass: 49.43-72.11 kg), Dempster quantified both segmental centres of gravity with a balance plate and volumes using immersion methods. The mass moments of inertia of each segment were calculated around the transverse (through the COM) and parallel axes (through the centre of the proximal joint) by a free swinging pendulum system.

Using similar techniques as detailed by Dempster (1955), Clauser et al. (1969) examined the segmental mass, volume and COM of 13 Caucasian male cadavers (49.31 ± 13.69yrs; 172.72 ± 5.94 cm; 66.52 ± 8.7 kg). Additionally Clauser et al. (1969) established a series of regression equations to estimate these segmental parameters, based on defined anthropometric measurements. These included the length, circumference and breadth/ depth of each body segment.

Chandler et al. (1975) dissected six male embalmed cadavers (age: 54.3 ± 7.3yrs, mass: 65.17 ± 13.20 kg and height: 172.15 ± 5.75cm) to measure the segmental mass, volume, COM location, and additionally calculated the principal mass moments of inertia of each segment. Anthropometric measurements were also obtained from both the entire cadaver and individual segments. The methods used to calculate the 116 anthropometric measurements and the segmental properties resembled those of Clauser et al. (1969). Some of the results from this study were compared to data collected by Santschi et al. (1963) on living subjects and it was concluded that a satisfactory level of agreement exists between the two datasets. Nevertheless, Chandler et al. (1975) expressed caution that their data should not be interpreted to reflect population parameters due to the limited subject sample. Others consider their data the most valid estimates of the segment moments of inertia available at the present time and can be used as a criterion for comparing other estimates (Miller and Nelson, 1973; Jensen and Nassas, 1988).

2.4.3.1.1. Limitations with Cadaver data

Despite the initial breakthrough in obtaining data from cadaver studies, there are many concerns over the interpretation and implementation of the results. The literature firstly highlights whether cadaver data can be reasonably applied to living subjects. The density of tissues in cadavers differs from that of living subjects (Katch and Gold, 1976; Zatsiosky, 2002) which would introduce errors into the calculations. Despite this acknowledgement, many scientists are of the opinion that due to the impracticality of achieving such measurements on living subjects, applying cadaver data can be used as a rough approximation.

The second concern is with regard to the sampled population within these studies. The number of subjects per study was generally quite small due to obvious ethical restrictions. It is also considered that the populations sampled were not representative of the average adult population with respect to race, age, height or weight. Indeed the majority of the scientists who conducted the cadaver research often concluded that their data should be interpreted with caution (especially when applied to diverse populations) due to the inherent errors. Hence in situations where it is impossible to obtain direct data on individuals, cadaver data may be applied but the accuracy of the segmental properties are at best a first approximation and should be treated with caution (Katch and Gold, 1976; Plagenhoff et al., 1983).

2.4.3.2. Computation (Regression equations etc)

Due to the difficulty in ascertaining segmental characteristics from living subjects, regression equations have been formulated. Based on certain anthropometric measurements, these equations calculate the appropriate segmental information with minimal subject intrusion. Initially a fixed relationship, such as a percentage correlation, between the segment and that of the total body was assumed. These relationships have been determined from cadaver data. The advantage of this technique is that one does not need any prior anthropometric measurements on the subject being analysed, which makes this approach very fast and easy to use (Sprigings et al., 1987).

Combining cadaver data of Braune and Fischer (1889), and Dempster (1955) Barter (1957) presented regression equations that predicted the segment mass as a function of total body weight (Table 2.6).

Body Segment	*Regression Equation*	*Standard Error of Estimate*
Head, Neck and Trunk	= 0.47 x Total Body Wt + 12.0	(±6.4)
Total Upper Extremities	= 0.13 x Total Body Wt – 3.0	(±2.1)
Both Upper Arms	= 0.08 x Total Body Wt – 2.9	(±1.0)
Forearm plus Hands	= 0.06 x Total Body Wt – 1.4	(±1.2)
Both Forearms*	= 0.04 x Total Body Wt – 0.5	(±1.0)
Both Hands*	= 0.01 x Total Body Wt + 0.7	(±0.4)
Total Lower Extremities	= 0.31 x Total Body Wt + 2.7	(±4.9)
Both Upper Legs	= 0.18 x Total Body Wt + 3.2	(±3.6)
Both Lower Legs plus Feet	= 0.13 x Total Body Wt – 0.5	(±2.0)
Both Lower Legs	= 0.11 x Total Body Wt – 1.9	(±1.6)
Both Feet	= 0.02 x Total Body Wt + 1.5	(±0.6)

Table 2.6: Regression equations developed by Barter (1957). *N= 11, all others N= 12. Wt- weight

Due to differences in dissection techniques for the head and neck, Barter (1957) could not compute a regression equation for this segment and so recommended that the researcher use Dempster’s data. Clauser et al., (1969) also developed regression equations to predict segmental mass, but additionally incorporated 2-3 anthropometric parameters into the equations. The inclusion of specific anthropometric measures ‘personalises’ the data by taking into account the subjects’ proportionality differences and reduces the magnitude of error (Miller and Nelson, 1973). Regression equations that assumed a fixed relationship between the segmental length and the location of the segmental COM were also established by Braune and Fischer (1889), Dempster (1955) and Clauser et al. (1969).

Using radiation techniques, Zatziorsky and Seluyanov (1983) were able to analyse segmental mass and inertial characteristics (mass, location of COM and radii of gyration) of 100 healthy living young men (age: 23.8 ± 6.2yrs; mass: 73.0 ± 9.1 kg; height: 174.1 ± 6.2 cm). Based on the scans, average values and more than 150 second order regression equations for the mass, COM and principal mass moments of inertia of the body segments were derived. These regressions were supplemented by a further set in which segment anthropometric measures were used as predictor variables. Consequently the accuracy of prediction was improved by the use of segment-specific variables.

2.4.3.2.1. Limitations of regression equations

Whether based on direct proportions or regression equations, one can obtain information on segmental mass, mass centres and selected moments of inertia with ease. However, the source from which they were derived, namely a limited number of Caucasian adult male cadavers (with the exception of Zatziorsky and Seluyanov, 1983) must be kept in mind. When implementing this method, investigators should consider the lower degree of accuracy that one would expect from applying average values from a small population of cadavers to specific living individuals that might differ considerably from the cadaver population (Sprigings et al., 1987).

2.4.3.3. Radiation

This technique involves scanning the subject's body and subsequently retrieving surface density and coordinate data of the body which has been affected by radiation. These components are measurable based on the principle that photon transmission is dependent on the mass and composition of the body. Hence the magnitude of rays that penetrate the body will provide an evaluation of its mass.

Zatziorsky and Seluyanov (1983) developed the gamma-mass scanning technique to quantify the segment mass and its distribution directly. Using this method, the radiation was measured before and after it passed through the body, providing an indication of the segment density (the amount of mass below the surface area). As mentioned previously, having obtained these results, Zatziorsky and Seluyanov (1983) derived regression equations that permitted them to calculate the mass, COM locations and principal mass moments of inertia of the body segments.

Despite the inclusion of a younger and healthier population, de Leva (1996) highlighted that Zatziorsky and Seluyanov's (1983) data are rarely preferred to cadaver data, due to bony landmarks were used as reference points for locating the segmental COM and defining segment lengths. Some of these points are quite distant from the centres of the neighbouring joints, meaning that when a subject flexes their joints the distances of these reference points from the respective proximal or distal segment COM's significantly decreases (de Leva, 1996). These and other related changes which make it impossible to accurately locate segment COMs, can be minimised only by using joint centres as reference points (de Leva, 1996).

2.4.3.3.1. Computed Tomography

Computed Tomography (often referred to as a CT scan) is an alternate radioactive technique used to measure in vivo segmental inertial parameters. To commence the procedure, the operator obtains three-dimensional computer images of the body by using the CT scan machinery. Use of the 'standard picture recognition' tool, helps to identify the boundaries and cross sections of the internal organs and bones from the images produced. Based on the 'CT number distribution' in the cross-sectional scan, the outlines of the anatomical structures can be automatically traced and their coordinates saved (Huang and Suarez, 1983). The mass, centre of gravity and inertia of each anatomical structure is then computed from the coordinates of the outline and the conversion of the enclosed CT numbers to mass densities (transforming the CT numbers to its mass density is performed by converting pixel by pixel). Studies have shown that there is generally good agreement between the CT-derived bone, muscle and fat density values in comparison to traditional methods as described previously (Ackland et al., 1988; Huang and Wu, 1976). For example, when comparing CT scans of a patients and a cadaver's leg segment, Ackland et al. (1988) found that there was a 1.9% difference between the CT-derived density values and the hydrostatic weighing values for the cadaver leg. Rodrigue and Gagnon (1983) also employed CT to estimate the forearm density of 20 human cadaver segments. They calculated density and volume estimates that were within the range of 0.1-4.8% and 5.4-35.9% respectively, of the criterion values obtained by direct measurement. Concomitant to the good results and the advantages of this method, as outlined in Huang and Suarez (1983), it would appear that both gamma-scanning and CT techniques offer promising methods for estimating body segment characteristics in vivo.

2.4.3.3.2 Limitations of Radiation

Despite the potential these techniques offer, they are rarely incorporated into research studies for two reasons. The primary limitation is because CT imaging and gamma mass scanning are radiation-based. Even though the radiation levels are low, they still present a risk to the subject being analysed to adverse effects of exposure. Secondly the costs, qualification of the operator and time commitment these instruments incur have prevented common utilisation.

2.4.3.4. MRI

Magnetic resonance imaging is a relatively new method of obtaining cross-sectional images of body tissue distribution within segments without exposing it to radiation. The principle of this technique is based on the magnetic moment (dipole) generating an electromagnetic force that is detected by a receiver coil interfaced with a computer. Computer generated pictures depict the cross-section of the body through which the magnetic field passes. Each tissue shows up as specific shades of brightness (white to black).

Martin et al. (1989) and Mungiole and Martin (1990) examined segmental parameters, as quantified by the MRI scan, which closely agreed or came within the range of other predictive methods. Using eight baboon cadaver segments Martin et al. (1989) examined the mean differences (%) between MRI values and those obtained from direct measures for the volume, density, mass, COM location and moment of inertia, which were found to be 6.3, 0.0, 6.7, -2.4 and 4.4% respectively. Mungiole and Martin (1990) examined the lower leg inertial properties for 12 adult male athletes (age: 28.59 ± 3.41yrs; mass: 66.24 ± 3.72 kg; height: 177.69 ± 4.54 cm) using the MRI technique. The MRI-based estimates, especially the COM data, all fell within the range of values obtained with other methods. Moreover, in addition to obtaining comparable or better body segment inertial parameters with the MRI technique- the fact that inertial properties of any portion of the body can be obtained safely and accurately is a major advantage (Martin et al., 1989). This is particularly beneficial when calculating the trunk and head segments which have, in the past, presented problems to previous researchers.

However, similar to the gamma-mass scanning and CT scan method, the limited facilities for MRI analysis, the high cost and time consuming nature of the analysis does not make this method very practical for determining inertial properties in vivo.

2.4.3.5. Mathematical Modelling

By employing simplifying assumptions concerning the composition and functioning of the body, in addition to technological advancement of computer programming and software, the development of mathematical modelling techniques has emerged. The advantage of this technique is that biomechanical properties of all segments can be obtained readily from few anthropometric measurements of the subject. As a result, subject invasion and time commitment are greatly reduced. This technique is particularly useful for the kinetic analysis of sport because extensive calculations of the body segment parameters can be obtained quickly and accurately.

The underlying assumption of mathematical modelling is that each body segment can be represented by a simple geometric shape. The second assumption is that each segment has uniform density as determined from the cadaver data. There has been much speculation as to the authenticity of applying this assumption. Indeed Ackland et al. (1988) confirmed that the assumption of segment uniform density was invalid based on the 10% variation in density along the segment length. However, Ackland et al. (1988) further showed that the adoption of the uniform density assumption when estimating inertial parameters of leg segments only produced minor errors and was therefore acceptable. Furthermore, Mungiole and Martin (1990) using MRI techniques, observed less variation in segment density (2.3%) along the longitudinal axes of the leg, which strengthens the support of the uniform density assumption.

Regardless, the fundamental disadvantage of this technique is that its application is limited to adult male subjects due to the fact that the mass distribution relationships have been derived from a relatively small sample of cadavers.

2.4.3.5.1. Hanavan's 1964 Model

Hanavan (1964) devised a 15-segment computerised model (Figure 2.7) which depicted the head as a circular ellipsoid, the two trunk segments as elliptical cylinders, the hands as spheres, with the subsequent segments represented as circular cones (Bartlett, 1999).

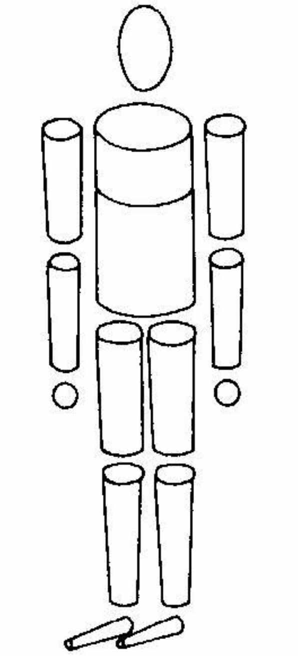


Figure 2.7: 15 segment model as designed by Hanavan 1964.

Twenty-five anthropometric measurements, including body weight, height, segment lengths and girths were inputted to the program to personalise the model for each subject. Hanavan also incorporated Barter's (1957) regression equations, based on 12 cadavers, to estimate the segment masses. Hanavan computed the segmental and total body principal moments of inertia and COM location. Miller and Nelson (1973) highlight that because it was Hanavan's intention to calculate the inertial properties of the total body in various positions, data of individual segments was not outputted. However, it is acknowledged, that by using subroutine calculations, one may obtain these quantities (Miller and Nelson, 1973).

In order to validate the Hanavan model, comparisons were made between the COM locations and relative segment densities for model segments and the cadaver data of Dempster (1955). The COM location errors in the average values of the Hanavan model were quite low, with the exception of the head-torso and upper arm segments. Discrepancies in relative density were as high as 10% and greater for the foot.

Comparisons were also made with results obtained experimentally from 66 subjects (Santschi et al., 1963). According to Bartlett (1999) the values of whole body COM location were such that only 50% of the predicted model horizontal and vertical locations were within 1.3cm and 1.8 cm respectively of the experimental data. The moment of inertia errors were greater, with only half of values about the two horizontal principal axes being within 10% of the experimental values. For the vertical axis, a discrepancy of less than 20% occurred for only half of the data.

There are many limitations for this model, primarily the substantial errors identified in segment volumes and moments of inertia. Bartlett (1999) suggests these are due to oversimplified geometrical shapes utilised to represent the human limbs and the uniform density assumption. Jensen (1978) supported the above by adding that the assumption of simple geometrical shapes does not take into consideration the shape fluctuations throughout the segment length which results in questionable accuracy. Secondly this model did not incorporate movements between the head and trunk segments or distinguished the shoulder girdle segments- both would be utilised in sports motion. Miller (1979) concludes that modifications of Hanavan's model are required to improve its accuracy and segmental moments of inertia.

2.4.3.5.2. Hatze's 1980 Model

Hatze (1980) developed a similar model to that of Hanavan, but further incorporated the two shoulder girdle segments, to produce a 17-segment mathematical model (Figure 2.8). The model was personalised by inputting 242 anthropometric measurements for each subject.

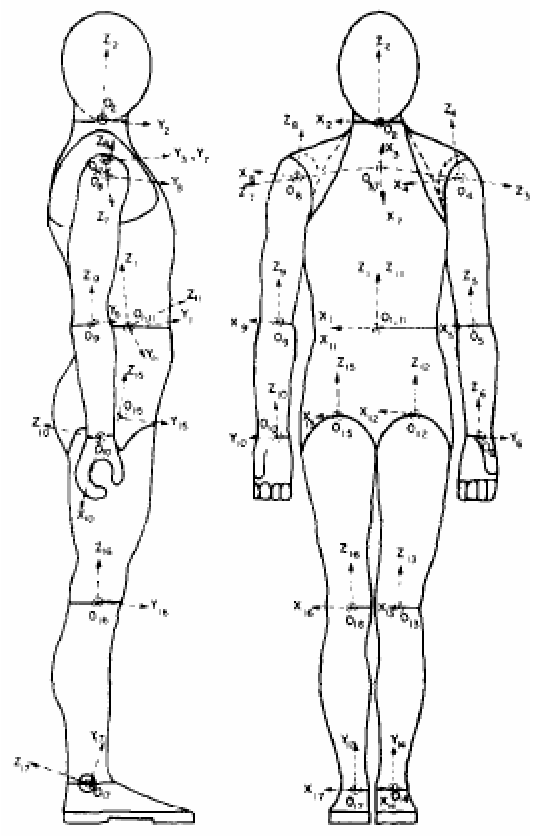


Figure 2.8: Lateral and anterior view of Hatze's 1980 17-segment anthropomorphic model. The shapes of the segments, as depicted here, accurately reflect the morphologies of the model segments. The local (segment fixed) coordinates are also shown.

Hatze (1980) claimed that his model was superior to other previous models because it allowed for sex differences by use of different density functions and mass distributions and the fact that segments had neither simple nor symmetrical shapes. For example, when analysing the model, each segment was subdivided into subsections of known geometric structure, each having a specified density- thereby allowing density distributions along and across the segments to be incorporated (Bartlett, 1999). To evaluate the accuracy of this mathematical model, Hatze reported model predictions on four anthropometrically diverse subjects (two young male athletes, one female tennis player and one 12year old boy) and compared this data with experimental measurements from four subjects as reported by Dempster (1955).

It was concluded that the overall accuracy of the program was approximately 3%, and subject to a maximum error of about 5% for each of the 17 segments. One of the many examples detailed by Hatze (1980) to illustrate the above can be seen within the average error results between the measured and computed total body mass which was reported as 0.06%.

Sprigings et al. (1987) further supported the above claims by commenting that Hatze's anthropometric model was more accurate at predicting the subject's centre of gravity than Dempster's (1955) data or Clauser et al.'s (1969) percent segment input data. The fact that the execution time of the computer program took only 0.515 secs is recognised as an additional bonus (Hatze, 1980)

Despite the reported accuracy of this mathematical model, it does contain obvious limitations. It is recognised that the time required to gather 242 anthropometric measurements takes approx 80mins/subject (Hatze, 1980; Sprigings et al., 1987; Bartlett, 1999). This would have considerable implications if the researchers required data from a large sample and would be tedious for the subject involved. As a result, Sprigings et al. (1987) recommend that the researcher should decide whether the improved accuracy by Hatze is warranted by the extra hours of subject measurement.

2.4.3.5.3. Yeadon's 1990 Model

Yeadon (1990) developed a model that divided the body into 11-segments with the assumption that the segments are rigid and that no movement occurs at the neck, wrist or ankle joints. Similar to Hatze's model, Yeadon subdivided the body into 40 sub segments and included 95 anthropometric measurements (34 lengths, 41 perimeters, 17 widths and 3 depths), which Yeadon claimed took 20-30mins.

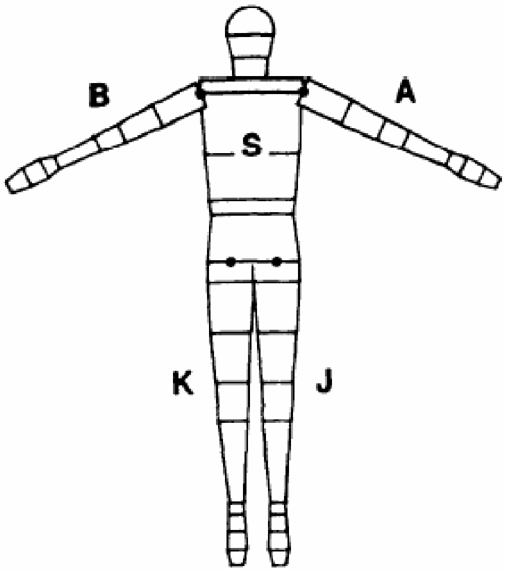


Figure 2.9: Yeadon's 1990 Model; Sectioning of the torso S. Left arm A, Right arm B. Left leg J and Right leg K into 40 solids.

The solids representing the torso, hands and feet are stadium solids, whereas the head, arms and legs are represented by a circular cross-section. For each segment the mass, COM location, principal moments of inertia about the mass centre and distance between joint centres are calculated. It is assumed that the solids comprising a segment have coincident longitudinal axes. The values for the left and right limbs are then averaged since the simulation model is designed to have symmetrical inertia values.

Dempster's cadaver density values were incorporated into the calculations, which Bartlett (1999) recognises as a limitation of the model. Three trampolinists (two male and one female) were used to evaluate Yeadon's model. Comparing the measured total body mass to the predicted estimates, resulted in an error close to 2%, which was more than Hatze's results (Table 2.7).

Subject	*Mass (kg)*	*Estimated Mass (kg)*	*Error (%)*
A	60.0	58.8	-2.0
B	60.9	62.0	1.8
C	64.3	65.8	2.3

Table 2.7: Total body mass from Yeadon 1990 model compared to those obtained by weighing. Adapted from: Yeadon 1990.

Evaluation of this model's accuracy with regard to segment inertial parameters has not yet been conducted and therefore cannot be compared against the Hatze (1980) or Hanavan (1964) models. Nevertheless Bartlett (1999) suggested that this model may potentially be a suitable compromise between Hanavan's (the errors were too large and oversimplified for modelling and simulating sports motions) and the over-parameterised model of Hatze (1980). However, the accuracy of the model has not been established sufficiently to use it with confidence.

2.4.3.5.4. Jensen's Elliptical Zone Method

Jensen (1978) developed a 16-segment model in which the segments were considered to be composed of elliptical zones 2cm wide. Subdividing each segment in this manner allows the model to detect shape fluctuations within the segment. Segment densities are assumed and used with the calculated segment volumes to give the segment masses. The assumption that the body is composed of elliptical zones had been applied by Weinbach (1938) and verified by Dempster (1955) as reasonable with the exception of the shoulders. Segment densities were assumed to be uniform and as reported by Dempster (1955).

After marking the subjects anatomical joint centre reference points and the lines to identify the segment sections they were placed on a horizontal board, lying in a prone anatomical reference position (Jensen, 1978). Two photographs were then taken of the subject one from the frontal view and the other from the lateral view. The two images are then analysed by digitising the required points and the size and inertial parameters computed. This process is initiated by sectioning the segments into 2cm ellipses and subsequently calculating the radii from both the front and lateral views. The volume, mass, COM location and moments of inertia of each elliptical cylinder is then calculated by implementing the formulas given by Jensen (1978). Segment mass is obtained by summing the masses of the elliptical zones within each segment. The location of the segments COM is determined by summing the moments of the elliptical zones using the positions of the centroid of the cylinders with respect to the proximal endpoint as the moment arm (Deffeyes and Sanders, 2005). Finally, the moment of inertia of the segments are determined for the anteroposterior, medio-lateral and proximal-distal axes of the segment by summing the local and remote moment of inertia terms in accordance with the parallel axis theorem (Deffeyes and Sanders, 2005).

Jensen (1976) compared results obtained from the elliptical zone method to those obtained by Hanavan's model. The largest differences were for the segments with irregular shapes. This supports the opinion that the elliptical zone method can accurately detect shape fluctuations.

On a whole, researchers who have utilised the elliptical zone method for calculating body segment parameters have presented relatively accurate results. Jensen (1978), comparing three prepubescent boys of differing somatotypes, found that the elliptical zone method showed an error of less than 2% compared to the measured body mass (Table 2.8).

	Ectomorph	*Endomorph*	*Mesomorph*
Estimated Body Mass (kg)	28.83	40.72	39.21
Measured Body Mass (kg)	28.50	40.25	40.00
Error (%)	1.16	1.17	1.82

Table 2.8: Accuracy of the estimate of total body mass compared to that obtained from weighing scales. Adapted: Jensen 1978).

According to Jensen (1978), in a subsequent study of 12 subjects ranging in age from 4-12yrs, the error for the Hanavan method was -12.36% compared to 0.68% for the elliptical zone method (a negative error signifies the model underestimates the actual model). Jensen (1978) reported that based on these results, the elliptical zone method is more accurate when applied to children. Moreover, Yokoi et al. (1985) obtained body segment parameters from 184 (93 males, 91 females) Japanese 5-15yr old children using the elliptical zone method. The average differences between the estimated (using elliptical zone method) and the measured values for the body was 1.14% whereas for the whole body, the error in COM location was 1.82%.

Jensen (1986) studied a group of 12 boys between the ages of 4-15yrs over a period of three years and thus obtained 36 observations. The mean errors were 0.203% with a standard deviation of 2.301% between the predicted body mass and the measured body mass. Jensen and Nassas (1988) reported errors of -0.82% (SD= 2.63%, N= 88) in the total body mass of 12 boys (4-20yrs) taken over a nine year period.

Sanders et al. (1991) employed the elliptical zone method and found that all mass estimates were within ± 3% (Table 2.9). These are comparable to errors in mass estimates previously reported by Jensen (1978) of 1.13, 1.17 and 1.82%, and are within the standard deviations reported by Jensen and Nassas (1988) of 2.63% (n= 88).

Subject	*Sex*	*Age (yrs)*	*Mass (kg)*	*Stature (cm)*	*Est. Mass (kg)*	*Error (%)*
1	F	35	63.8	167	64.8	+1.3
2	F	24	60.6	165	62.1	+2.5
3	M	21	76.4	175	75.5	-1.2
4	M	28	82.9	179	81.9	-1.2

Table 2.9: Participant characteristics and accuracy of the estimate of total body mass, compared to that obtained from weighing scales. (Adapted: Sanders et al. 1991).

Wike and Lopers (2003) examined the validity of the volume functions of Jensen's elliptical zone method on testing 20 subjects: 10males (24.3 ± 1.4yrs; 178.8 ± 6.6 cm; 75.4 ± 9.5 kg) and 10 females (23.8 ± 1.4yrs; 161.4 ± 6.1 cm; 62.7 ± 10.9 kg). They also concluded that the volumes of several segments, as well as the whole body, can be accurately measured using the elliptical zone method.

From the aforementioned studies, it appears that Jensen's elliptical zone method offers an accurate means of calculating the subjects body segment parameters. Yet Deffeyes and Sanders (2005) recognised that its implementation within studies is not common because of limited availability of digitising tables and data collection programs which are compatible with the digitising device. Consequently a PC based digitising software program known as 'eZone' was developed that combines the functions of digitising digital photographs to obtain the diameters of the ellipses, with the ability to calculate the BSP data. The eZone program uses the same procedure and methods as those established by Jensen (1978) and is estimated to take 10-15mins to complete the process.

On evaluating this new program the authors reported the BSP values to be within the ranges expected based on the literature, with the whole body mass within 5% of its actual value. Further Psycharakis (2006) reported the mean differences (for the group of swimmers) between calculated and real values for the whole body mass as -0.2 ± 0.9 kg or -3 ± 1.3% (expressed as a percentage of the real body mass values). It is therefore reasonable to state that the eZone program offers a method of obtaining accurate anthropometric data. When combined with precise digitising of a whole body model it may be expected that the derived COM position data would yield COM velocity data of acceptable accuracy.

2.4.4. Net Accelerations

Buchner and Reischle (2002) stated that it is not sufficient to analyse swim performance based only on velocity curves of the swimmer and that the derived acceleration profiles should also be considered to allow a ‘more direct analysis of propulsion effects of movement actions than the velocity curves’. Mason et al. (1989) added that the acceleration profile indicates *where* the swimmer utilises effective propulsive actions to propel forwards and *where* effective streamlining is used to reduce drag. On the other hand, velocity profiles indicate the *effect* of propulsion on the swimmers motion (Mason et al., 1989). Buchner and Reischle (2002) commented that the time difference between maximum acceleration and maximum velocity, depends on the shape of the acceleration curve.

Nevertheless, as highlighted previously, an acceleration of the COM indicates that the propulsive forces are greater than the opposing resistive forces. There are periods of marked acceleration and deceleration within each SC, which are measured by tracking the forward velocity of the hips, or more accurately, the velocity of the COM (Maglischo et al., 1989). The majority of the literature indicates that maximum COM acceleration, which corresponds closely to maximum propulsion, occurs during the last phase of the underwater SC in front crawl, backstroke, and butterfly (Maglischo et al., 1989; Rouard et al., 1996; Cappaert, 1998; Maglischo, 2003). However, no quantitative data have been provided to illustrate this conclusion. Based on visual observation, Maglischo et al. (1989) commented that the COM decelerates during the downsweep and outsweep phases due to water being displaced to the side and down as opposed to directly backwards, but again no quantitative data were presented, and the activities of the opposing arm were not considered.

Generally there is a dearth of literature with regard to COM acceleration profiles in front crawl swimming. This is due to the difficulty of calculating the COM accurately throughout the SC and to present quantitative data to support qualitative analysis. Moreover, the COM acceleration profiles for specialised race distance swimmers, or swimmers performing over varying swim velocities, have not been discussed in the extant literature. Consequently, it is unknown whether sprint and distance swimmers have different COM acceleration profiles and whether these characteristics change between swim velocities.

2.5. Summary of Literature Review

While there are some indications of differences in the kinematics of sprint and distance swimmers the situation remains unclear, particularly with respect to the influence of distance specialisation. A digest of the literature reveals some evidence and belief that sprint swimmers stroke with a greater elbow angle (less flexion), stroke depth, spend more time in propulsive phases, use a six beat kick, a smaller total body roll and display a higher COM velocity fluctuation and acceleration profile than distance swimmers. Also, it has been reported that distance swimmers tend to exhibit a greater horizontal and lateral displacement of the arms, utilise a two beat kick, spend more time in the non-propulsive phases, have greater body roll and a smaller COM velocity fluctuation than sprint swimmers. Most of these conclusions have been based on qualitative observations and confirmation is required through quantitative empirical research. Most of the existing quantitative data has been obtained using methods with limited accuracy and reliability and most has involved two-dimensional rather than three-dimensional analysis techniques.

While there has been some comparison of the kinematics of sprint and distance swimming there has been no research into the effect of race distance specialisation on the kinematics of sprint and distance swimming. Thus, it remains unclear whether sprint and distance specialists differ in their kinematic characteristics, or whether the differences previously observed between sprint and distance swimmers are due only to the effect of the swimming pace. This issue will be addressed in this study using three-dimensional analysis methods to ensure confidence in the results.

Chapter Three: Methodology

3.1. Participants

A total of 15 male freestyle swimmers, (aged: 17.87 ± 2.33 years; body mass: 73.92 ± 8.72 kg; height: 183.02 ± 6.84 cm) volunteered from several Scottish and Northern Irish swimming clubs for this study. The sample included swimmers who currently compete in specialised events (7 sprint (50-100m) swimmers (SG) and 8 distance (400m+) swimmers (DG)) at national and international level. The sample was limited to elite trained swimmers to increase the likelihood that stroke characteristics and stroke patterns would be well established and consistent (Pyne et al., 2004; Nikodelis et al., 2005). The inclusion criteria for the subjects' participation were as follows; a) must be either a male sprint or distance specialist front crawl swimmer, b) must be specialised in their chosen distance event for a minimum of 2 years, c) sprinters personal best time for 50m, short course, must be less than 24.60secs, d) distance swimmer's personal best time for 400m, short course, must be less than 4min 10secs, e) at the time of testing, swimmers must have no injury, nor be in the process of recovering from one. The specified times above were based on the 15 best performances at the Scottish National Short Course Championships, 2007, for both the 50m and 400m freestyle events (See Appendix A for subjects' performance times).

The literature highlights many factors which affect sports performance, namely: heavy/overtraining (Lehmann et al., 1993), ingestion of caffeine and alcohol (Costill et al., 1978; Graham and Spriet, 1991; Shirreffs and Maughan, 1997; Burke et al., 2003), dehydration (Saltin, 1964a; Saltin, 1964b), and lack of sleep (Reilly and Piercy, 1994; Blumert et al., 2007). To prevent any of these factors affecting the swim test, participants were asked to avoid all of the above prior to the testing session.

Prior to all testing sessions, participants were provided with a volunteer information document (Appendix B), which details a brief purpose of the study, the requirements of the participants, and the protocol of the experiment. The possible risks the subject may experience and the benefits for their participation were also outlined. Subsequent to reading the volunteer information document, and the investigator addressing any concerns expressed by the participants, the swimmers (or the participants parent/

guardian if under 16yrs) signed the supplied informed consent form (Appendix B). Subjects were also required to complete a ‘pre- activity questionnaire’ based on the recommendations provided by the American College of Sports Medicine (ACSM, 2005). This form evaluates the participants’ medical readiness to undertake the physical activity required, and thus provides the investigator with the assurance that the participant is ready and able to participate in the rigors of the assessment.

To protect the swimmers’ identities, a code system was utilised to replace their names and any individual details of the swimmers. Thus, the code given to each swimmer, rather than the names used, is used throughout this thesis.

3.2. Participant Preparation

All participants wore brief swimming trunks so that the hip joint was clearly visible and easy to identify. An added benefit of wearing this type of swim costume is to reduce any effect of drag that ‘training’ trunks offer. As this study was conducted during the training phase of the swimmer’s program, they were not asked to shave down.

Once the swimmers had changed into their swimming trunks, their height and body mass measurements were recorded using the stadiometer (Seca 225-1821009) and weighing scales (Seca 712-1321009) respectively.

Participants were marked for two purposes: i) to track the swimmer through the water as they swim and ii) to enable subsequent calculation of the inertial properties of the limbs using the elliptical zone method (Jensen, 1976). Beforehand, both sides of the trunks were taped to reduce the possibility of obscuring the hip marker during the test (Figure 3.1).

Figure 3.1: Trunks taped

In swimming research skin markers are the most commonly used method to define the relevant limbs to be studied. In this study, black waterproof oil and wax based cream (Grimas Crème Make Up), applied by a 45mm diameter sponge was used to mark the participants' anatomical landmarks. Black was chosen due to the strong contrast with respect to the skin and water. All markers applied to the skin corresponded to the axis of the particular joint centre.

For the swimming trials, the markers required were: the vertex of the head and the right and left of the following: longest tip of the 3rd distal phalanx of the finger, wrist, elbow, shoulder, hip, knee, ankle, 5th metatarsophalangeal joint and the tip of 1st interphalangeal joint (Figure 3.2). The placement of these markers was carefully executed, to minimise errors in subsequent calculation of variables including the segment and whole body centre of mass. Moreover, markers were placed on the frontal and lateral aspects of the aforementioned markers so that they were visible to more than one camera perspective.

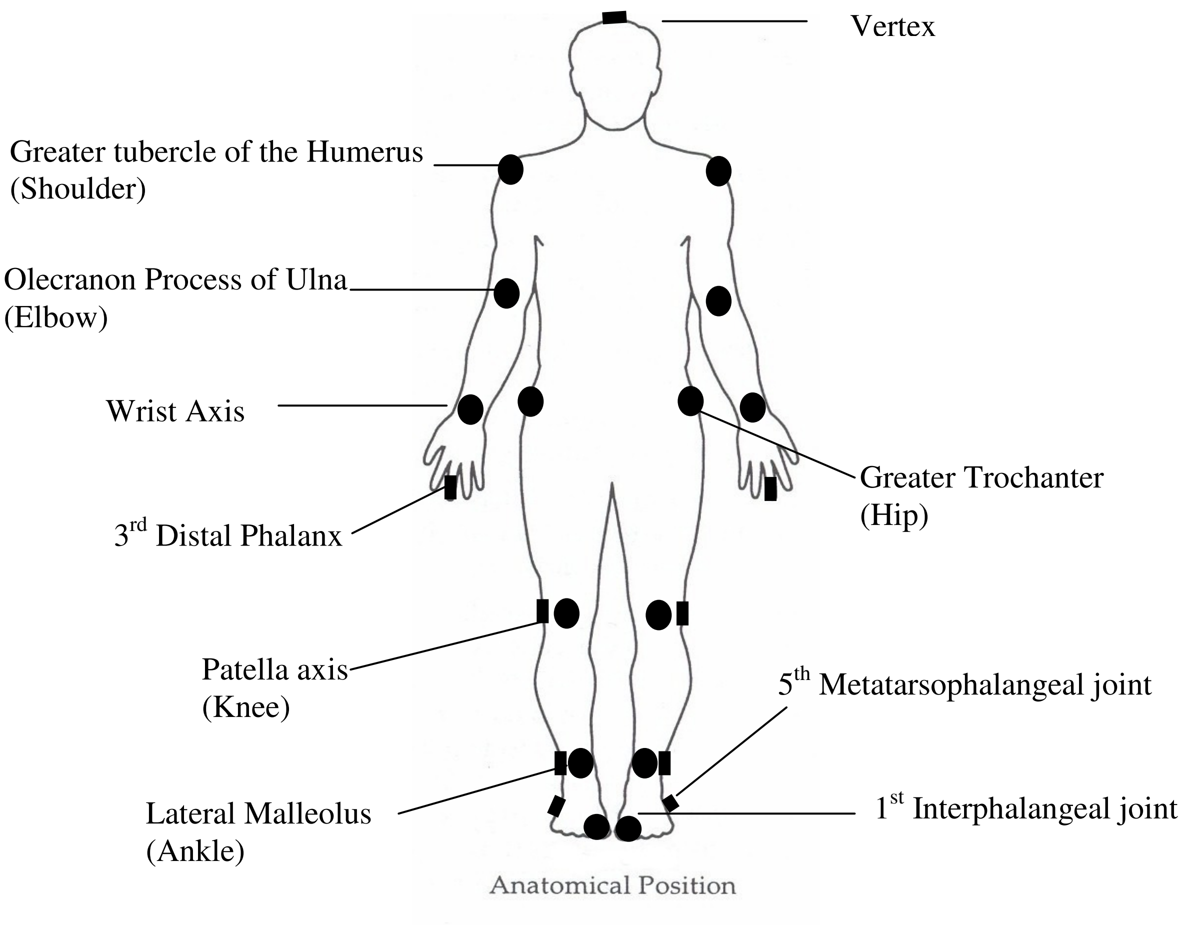


Figure 3.2: A model representation of the marker locations used during the swim trials.

For the calculations of the segment anthropometric data by the elliptical zone method (described later), additional markers were necessary to define the geometry of the body. As these markers were not required for the swimming trials, black tape was used. These additional markers were placed at the following locations: mandible angle, 2nd cervical vertebra, 7th cervical vertebra, axes of the head of each humerus, acromioclavicular joint, hip and the line of the xiphoid process (Figure 3.3). Additional information regarding the method of locating the above markers is provided in Appendix C.

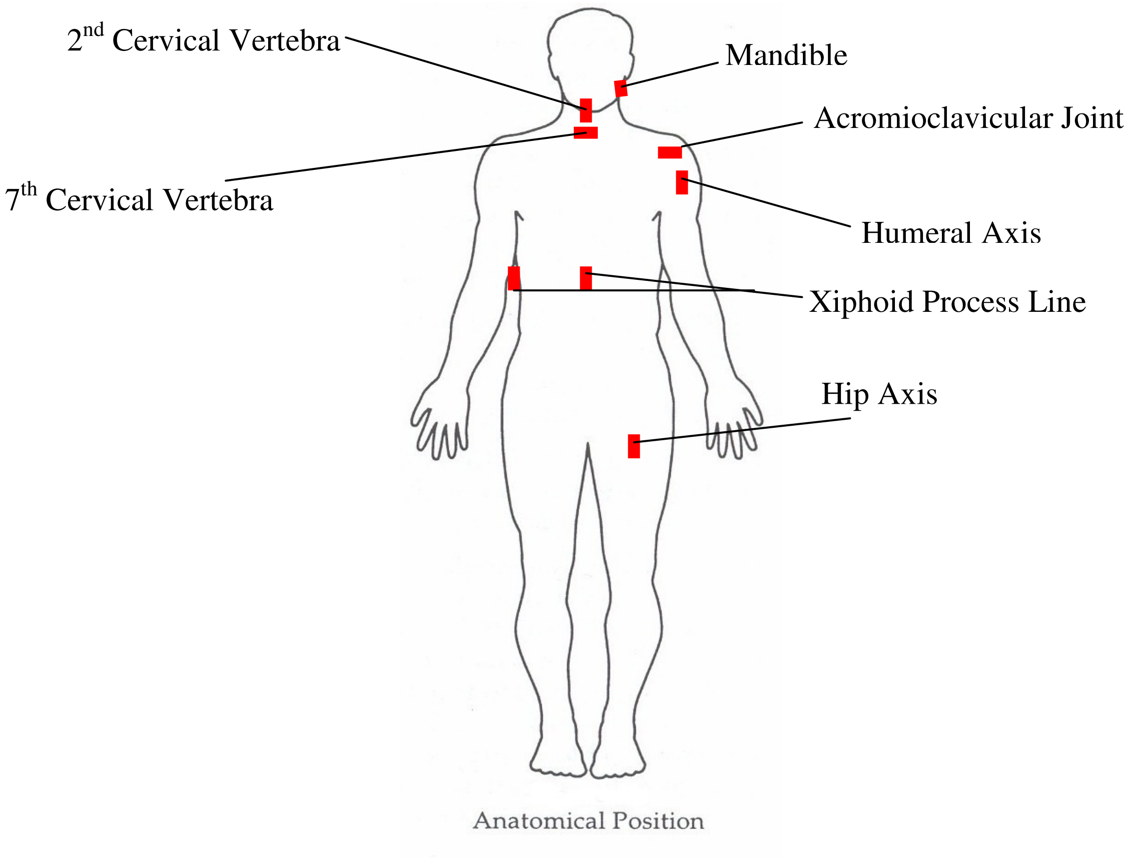


Figure 3.3: A model representation of the additional markers required for the eZone method calculations.

3.3. Experimental Design

3.3.1. Swimming Pool Details

The testing session was conducted in a 25m x 13.25m x 2m, indoor level deck swimming pool (average pool temp 29.5° ± 0.2 and air temperature 29.9° ± 1.2 over the testing period). Only one swimmer at any time was permitted in the pool during the testing session to minimise wave turbulence and prevent any possible interference with camera views. Wave turbulence was also minimised due to the nature of the swimming pool being level deck, which displaces excess water into the overflow channel perimeter (Figure 3.4). An added benefit of this type of wave turbulence reduction was the facilitation of the digitising process especially with respect to the above water camera views.

Evenly diffused and distributed lighting at 1000 Lux was provided by large lights and reflectors (Figure 3.4).

Figure 3.4: Trials were conducted in the above level deck swimming pool with adequate lighting.

Originally this swimming pool was specifically designed for aquatic research. Therefore, all underwater cameras were permanently fixed in the water in purpose built recesses in the pool walls. Transparent perspex protective screens which shielded the cameras were removed for video data collection to reduce errors due to distortion and refraction (Kwon, 1999; Kwon and Casbolt, 2006).

3.3.2. Camera Settings

Six ‘gen-locked’ JVC KY32 CCD cameras (4 cameras below and 2 above the water surface) recorded the motion of the swimmer. The above water cameras were mounted at elevated positions on the side walls of the swimming hall. The camera positions are shown in Figure 3.5.

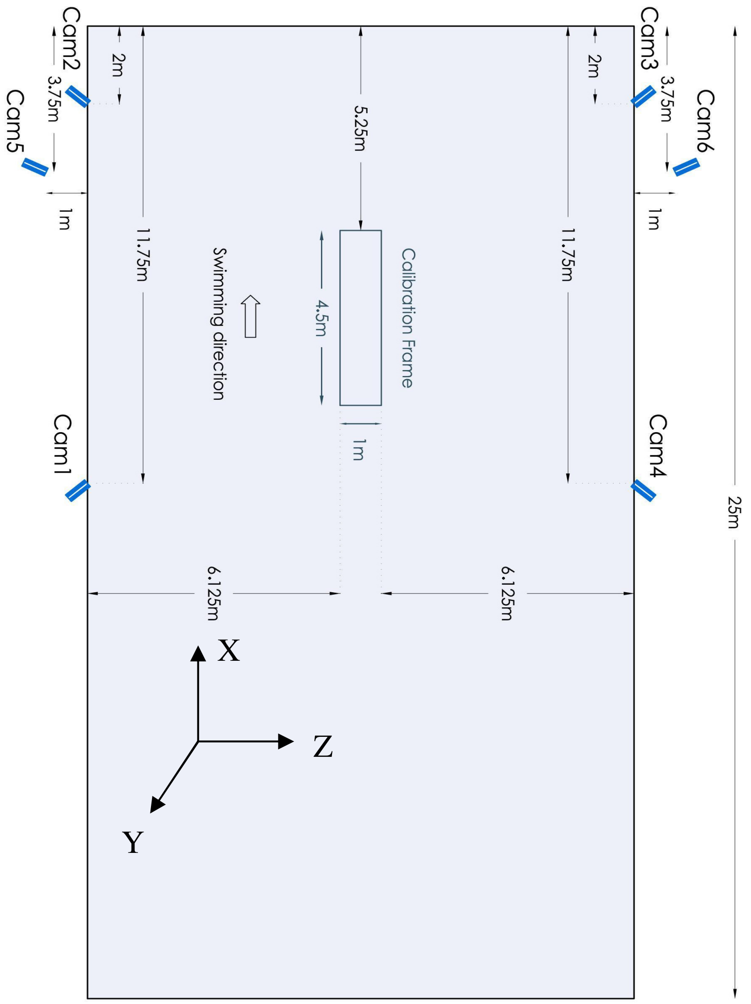


Figure 3.5: Camera and calibration frame set up during the testing session for 3D data capture. Cameras 1-4 are underwater. Cameras 5 and 6 are above water. X- horizontal direction; Y- vertical direction; Z- lateral direction. With permission from Psycharakis (2006).

Camera sampling frequency was set at 50 fields per second, with an electronic shutter speed of 1/120 seconds, sufficient to reduce the smearing/blurring of the image that occurs when recording fast movements such as swimming. High quality telephoto zoom lenses, provided almost perfect optics, i.e. minimal distortion, and enabled the field of view to be set to maximise image size while capturing one complete SC with every pass through the calibrated space. The gain function was also adjusted to obtain the best quality image possible prior to data collection taking into account the light levels of each camera view.

3.3.3. Calibration Frame

The calibration frame used in this study was designed and manufactured by The University of Edinburgh, based on the requirements for 3-D motion analysis (Figure 3.6). The dimensions of the rectangular prism frame were: 4.5m length, 1.5m height and 1m width, enabling a calibration space of 6.7m^3 in total. A sum of 92 (46 above and 46 below) polystyrene spheres (3cm in diameter), otherwise known as control points, were randomly distributed within the frame.

Figure 3.6 Picture of calibration frame.

Prior to each testing session, the calibration frame was positioned in the centre of the swimming pool. As swimming incorporates both above and below water movements, it was essential that the frame was elevated so that half of it was equally above and below the water surface. Eight aluminium legs, each 1.25m in length, were attached to the bottom of the frame via screwing the legs onto the external thread projected from the bottom of the base joints. The supports were adjusted so that the frame was aligned exactly with the external frame of reference with the x axes in the direction of swimming.

High accuracy and reliability of 3D coordinate calculation was established by Psycharakis et al. (2005). Using ten control points the mean difference for a set of thirty digitised points was: 3.3 mm, 2.6 mm and 4.0 mm for the X, Y and Z axes respectively. The average root mean square errors for these points were 3.9 mm, 3.8 mm and 4.8 mm for the X, Y and Z axes respectively, representing 0.1%, 0.2% and 0.5% of the calibrated space. Therefore Psycharakis et al (2005) concluded that the accuracy of the frame used in this study was similar or better than other frames used in 3-D swimming studies, due to the errors obtained being regarded as low and acceptable. The reliabilities indicated by repeated digitisations of one marker were ±0.4 mm, ±0.5 mm and ±0.4 mm for the X, Y, and Z axes respectively, also demonstrating good reliability in the reconstruction of 3D coordinates. In the same study, Psycharakis et al. (2005) also evaluated the effect of data collection with and without the transparent screens in front of the cameras. It was reported that data collection through the screens had a small effect. Nevertheless, in order to reduce all sources of error, data collection proceeded with the screens removed.

3.3.4. Testing Set Up

All underwater cameras have a height adjustment function that varies from 0.5m to 1.5m, as measured from below the surface of the water. The four underwater cameras used in this study were randomly fixed at different heights to avoid errors with respect to the camera axes being in the same plane as the axes of the calibration frame plane. It was also ensured that all the control points on the calibration frame were clearly distinguishable in order to enhance the accuracy of the digitising and subsequent calculations of the DLT coefficients. The two above water cameras were fixed at heights 2.5m and 3.5m respectively, as measured from the poolside deck.

Because the calibration frame was positioned in the centre of the swimming pool, all underwater cameras were approx 8m away from the centre of the calibrated space. The above water cameras were measured as being approx 12m away from the centre of the calibrated space. As in Psycharakis (2006) the angle between the 2 above water camera axes was approx 100°, while the angles between axes of adjacent below water cameras ranged from 75° to 110°.

All cameras were adjusted for a field of view of 6.5m length, which represented the full length of the calibration frame (4.5m) in addition to an extra 1m on both ends of the frame to ensure a full SC was captured. The vertical field of view was adjusted so that the swimmer was approximately along the midline of the view (Figure 3.7).

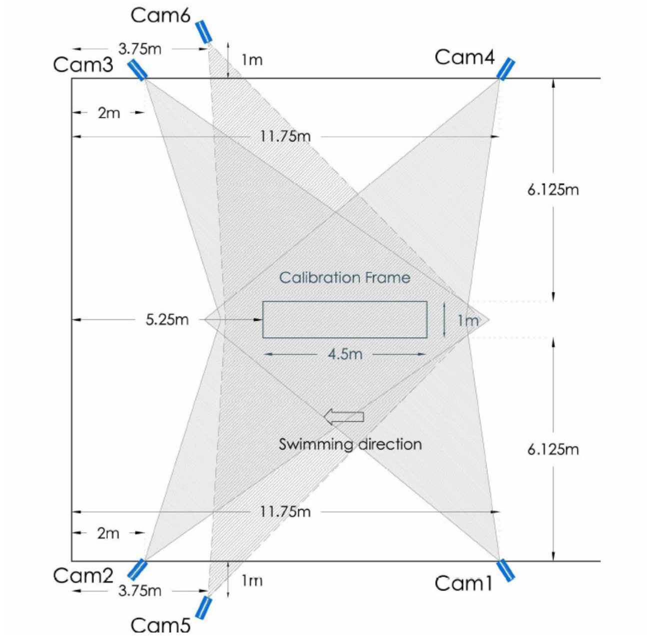


Figure 3.7: Cameras' field of view. Cameras 1-4 = underwater, Cameras 5-6 = above water. With permission from Psycharakis (2006).

After camera adjustments with respect to the calibration frame were made, the frame was video-taped for a period of 10secs (Figures 3.8 and 3.9). No person was allowed in the pool during this capture to ensure that there was no disturbance of the water that might interfere with the calibration process. Following this data collection, the frame was removed from the water and stored. No further adjustments were made to the camera settings at any time thereafter. During the testing session the participants swam in the space that the frame had occupied; this was marked by two black blocks outlining the beginning and end of the calibrated space. An added benefit of marking the space in this way was to indicate to the swimmers the area within which no breaths were to be taken.

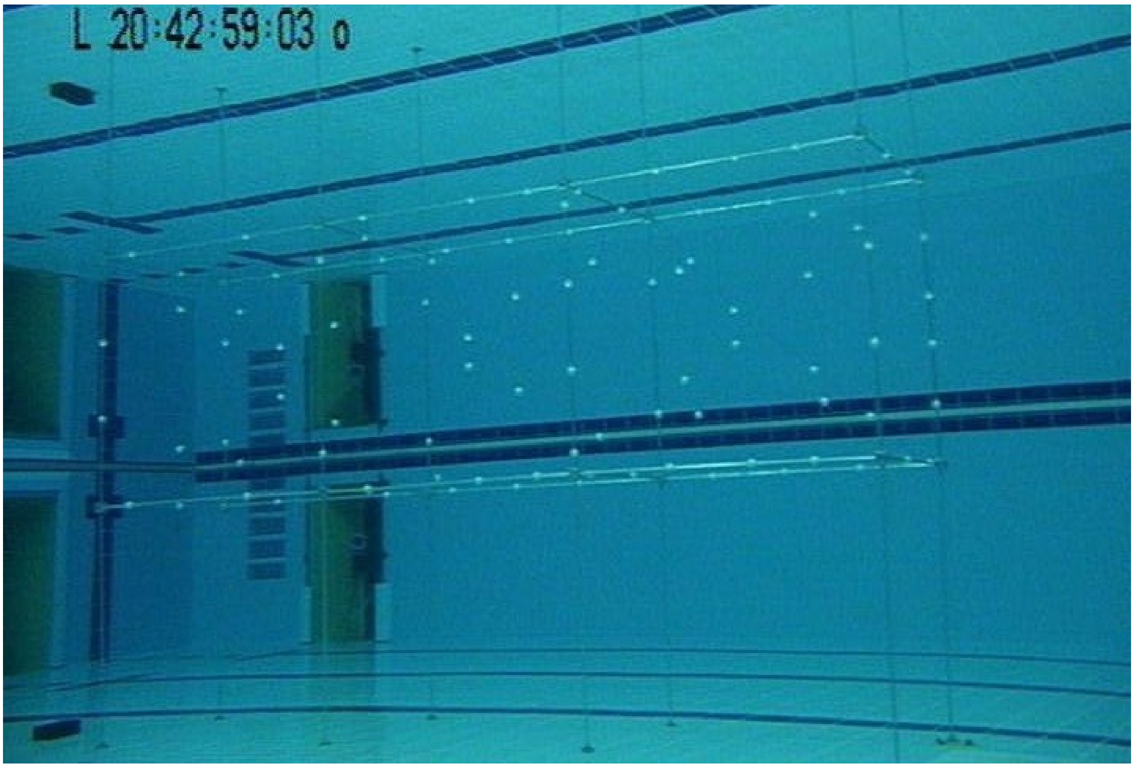


Figure 3.8: An underwater view of calibration frame from camera 1 perspective.

Figure 3.9: An above water view of the calibration frame from camera 5 perspective.

3.4. Testing Procedure

Data collection for each swimmer required one session. Due to the participants' vast experience, the swimmers performed their own individual warm-up prior to the testing session. Although individualistic in nature, this warm-up was still standardised and tended to last for a period of 10-15minutes, consisting of both aerobic and pace swimming, in addition to swim drills and stretching. As outlined in the literature review chapter this study had a 'no breathing requirement' within the calibrated space. Therefore, the swimmers were advised to familiarise themselves with this protocol during the warm-up.

After the warm-up, each participant was required to swim four repeat 25m sprints and one repeat 400m at a maximal effort and even pace. The order in which the swimmers performed the sprint block of trials and distance swim was randomly assigned to prevent any order effects.

All swim trials were performed in the centre of the swimming pool (which had been previously calibrated) and initiated from a push start to eliminate any possible influence that a dive may have on the stroke kinematics of the first length. Push starts are often used in swim research designs (Alves and Vilas Boas, 1992; Cardelli et al., 2000; Seifert et al., 2004a; Toubekis et al., 2005; Psycharakis, 2006). All trials were manually timed using a Cronus 602M100D stopwatch.

Each 25m sprint was accompanied by a recovery pace 25m to the starting position, followed by a two minute stationary rest period remaining in the water, before starting the next 25m sprint. At the completion of the 4 x 25m sprints, or the 400m maximum effort, swimmers were instructed to 'swim down' (swim at a recovery pace) for a period of at least 5minutes. Swimmers were then asked to exit the water and rest for a further 10mins on the poolside before warming up again to complete either the 400m maximum effort swim or the 4 x 25m sprints.

The recovery method utilised in this study was in accordance with research described in literature highlighting that active recovery, combined with passive recovery, and water immersion per se, following a bout of rigorous exercise, are more beneficial in terms of aiding the recovery process than passive recovery alone (Dodd et al., 1984; Choi et al., 1994; Wilcock et al., 2006).

3.5. Data Collection

3.5.1. Anthropometric Data

As described in the literature review, the elliptical zone method of Jensen (1976) was applied using software developed by Deffeyes and Sanders (2005), to quantify the anthropometric data of all the participants. The accuracy of calculating the COM of the whole body using the elliptical zone method from the anthropometric data obtained has been previously validated (Jensen, 1978; Yokoi et al., 1985; Jensen, 1986; Jensen and Nassas, 1988; Sanders et al., 1991; Wicke and Lopers, 2003). In simple terms, this technique requires two photographs taken simultaneously (from front and side views) of a marked participant, as described in the 'participant preparation' section.

3.5.1.2. Camera Setup and Capture for the Elliptical Zone Method

The two digital cameras used in this study were a Nikon E4200 and Canon Ixus 400, both with a 4.0 megapixel capacity. Although Deffeyes and Sanders (2005) recommended that a 2 megapixel digital camera is adequate for data collection, the higher resolution cameras used in this study would allow for a larger image-to-actual body size ratio, which would aid the digitising process and ultimately lead to a reduction in errors. Other functions of these cameras were: exposure time 1/60secs, ISO 200 and focal length 23mm. A flash was used to maximise image quality and contrast taking care to ensure that the flash did not produce shadows that affected the definition of the body segment outlines.

Both cameras were fixed to horizontally levelled tripods and set at a 1m height, based on the recommendation by Deffeyes and Sanders (2005) that the height of the cameras should be set at the equivalent of one-half of the participant's height. The axes of the cameras were horizontal and perpendicular to one another, so that both a front and side view of the participant would ultimately be observed simultaneously

(Figure 3.10). The perpendicular distance from the centre of the space to each of the cameras was set to 12m to minimise image distortion whilst maintaining a large image of the participant with the optical zoom function set at 3x.

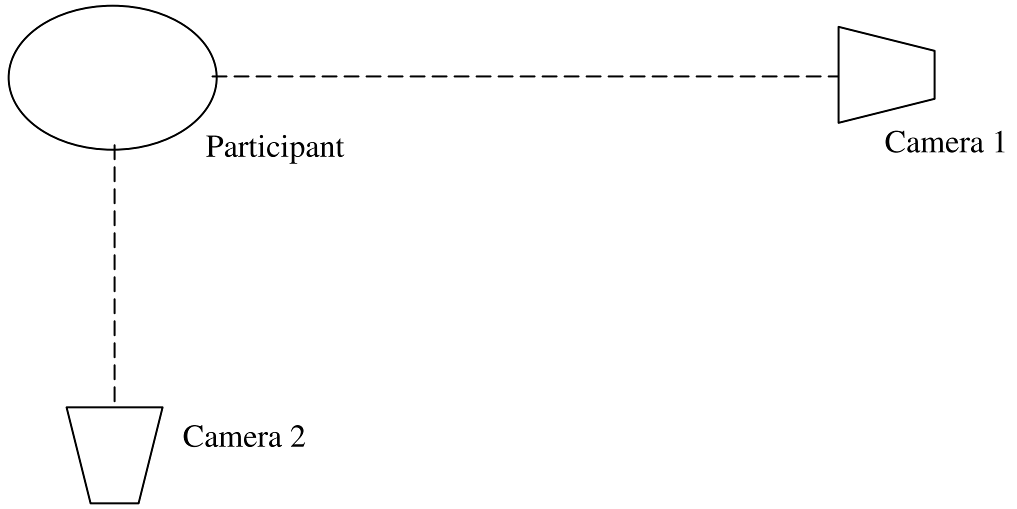


Figure 3.10: Schematic illustration (not to scale) of the participant and two camera set-up for the eZone method. Camera 1 captures the participants' front view. Camera 2 photographs the side view of the participant.

Prior to capturing the participants' photographs, the area was calibrated in order to convert pixels into 'real' distance for further data analysis in the MATLAB program. A vertical and horizontal reference scale comprising of a series of 200mm alternating white and black bands was positioned in the same plane as the participants' mid-frontal and mid-sagittal planes for the subsequent pictures (Figures 3.11 and 3.12). Camera settings were not changed between the calibration and participant photographs.

Figure 3.11: Side View of Calibration frame

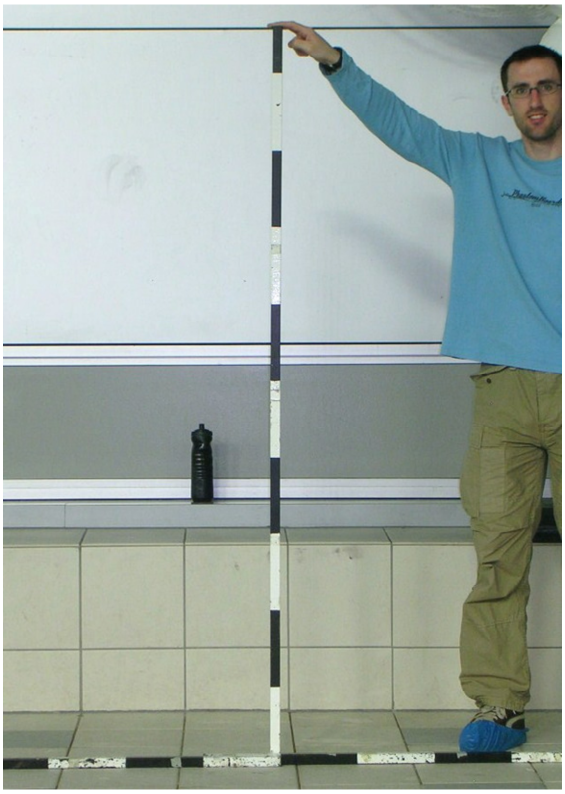


Figure 3.12: Front view of Calibration frame

The point at which the calibration frame was positioned was in turn replaced by four heavy kickboards, stacked to create an incline on which participants stood. Standing on an incline permitted the feet to be plantar flexed with the toes pointed, a prerequisite for elliptical zone calculations. Participants were instructed to stand in the anatomical position with the fingers and thumb adducted, hands held as straight as possible, and chin horizontally parallel to the ground. When viewed from the side the arms were aligned to avoid obscuring the outline of the torso and thigh. Participants were also required to wear a swim cap so that their hairstyle did not interfere with the outline of the head.

When the participants were satisfactorily in place, two photographs (front and side view) were taken simultaneously (not synchronised) with the help of another researcher (Figures 3.13 and 3.14). Taking the photographs simultaneously prevented errors being incorporated into the calculations due to the participant moving. These photographs were saved as ‘Jpeg’ files and input to a MATLAB program.

Figure 3.13: Front view of participant (eZone)

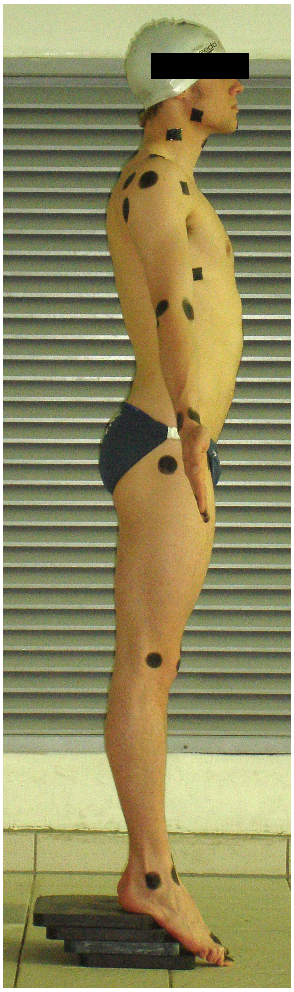


Figure 3.14: Side view of participant (eZone)

3.6. Data Processing

3.6.1. Anthropometric Calculation for Elliptical Method

The MATLAB 'eZone' program processed all the data collected by sequentially prompting the researcher for various inputs. Firstly, the program requested uploading the calibration frame photographs and which were then analysed by inputting the dimensions of the scales. Secondly, the participants' photographs were uploaded and the anatomical landmarks identified in response to the sequence requested by the program. This protocol defines the body segments and is completed for both the front and side views. Finally, the program requested that the following body segment clusters be outlined with the aid of the MATLAB image processing toolbox:

1. Head and Neck
2. Thorax and Abdomen
3. Thigh, Shank, and Foot (lower limb)
4. Upper arm, Forearm and Hand (upper limb)

After the above body segment clusters were defined, the eZone program divided these clusters into the head, neck, thorax, arm, forearm, hand, thigh, shank, and foot segments based on the digitised segment landmarks. A model representing the participant was then displayed on screen as seen in Figures 3.15 and 3.16:

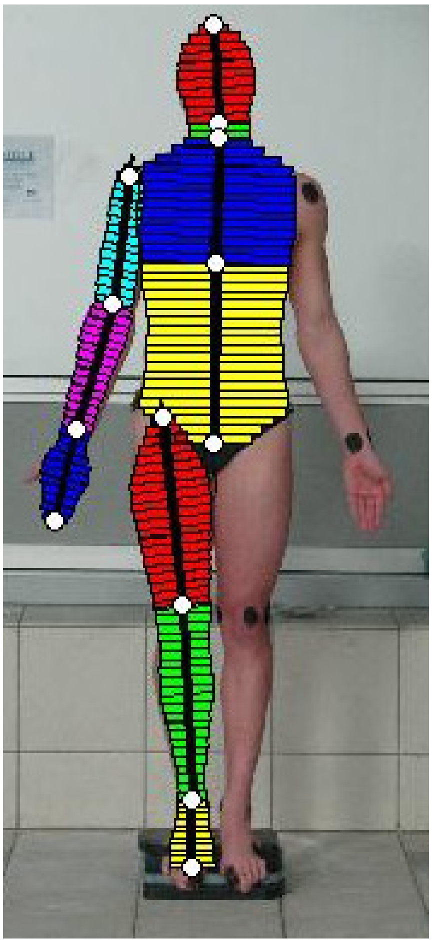


Figure 3.15: eZone model for Front View

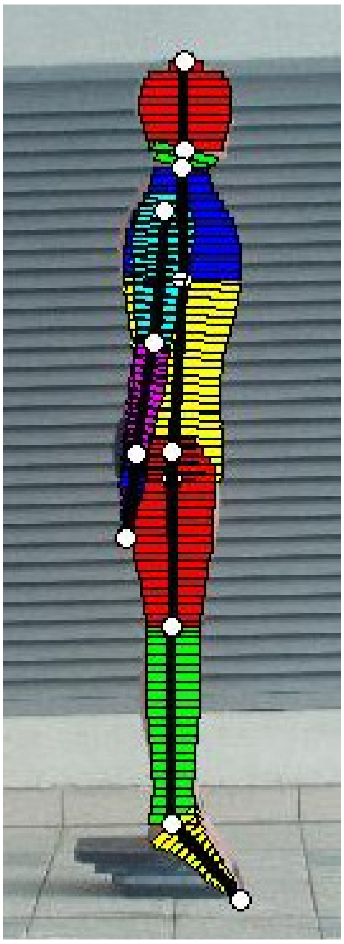


Figure 3.16: eZone model for Side View

It should be noted that during the data processing in MATLAB the images were magnified in order to ease the process of identifying the calibration scales, the anatomical landmarks and the outline of the body segment clusters. Magnifying the images is an acceptable method of analysing the data as Wicke and Lopers (2003) found that it reduced the digitising errors.

3.6.1.2. Accuracy and Reliability of Elliptical Zone Method

Psycharakis (2006) quantified the accuracy of the eZone program by measuring the difference of the body mass value as obtained from eZone calculations, to that obtained from 'real' (as measured from weighing scales) data for all 11 participants. It was reported that the mean (±SD) differences (for the group of swimmers) between calculated and real values for the whole body mass were -0.2 ± 0.9 kg or -0.3 ± 1.3% (expressed as a percentage of the real body mass values) (Psycharakis, 2006). In this study, the same calculations were performed and the differences were 0.12 ± 0.43 kg or 0.2 ± 0.6% between the values from eZone calculation and the real data. These results further support the high accuracy of the eZone body mass calculations, with differences smaller than other studies using the eZone method (Jensen, 1978; Yokoi et al., 1985; Jensen, 1986; Jensen and Nassas, 1988; Sanders et al., 1991; Wicke and Lopers, 2003; Psycharakis, 2006)

Reliability of the eZone calculations was also assessed by digitising the same participant 10 times. This procedure was completed by the same operator in order to eliminate any inter-operator errors. The SD of the body mass as calculated from the eZone program across all 10 repeats was 0.24 kg, or 0.31% of the mean body mass. Performing similar calculations Psycharakis, 2006, reported a SD for the whole body mass as 0.4 kg, or 0.3% of the mean body mass. It was therefore concluded that the eZone calculations used in this study had a reliability similar to those of Psycharakis (2006), with errors considered low and acceptable.

3.6.2. Digitising Swim Trials Procedure

The camera recordings of the swim trials were automatically converted to AVI files and saved to each PC hard drive dedicated to each camera. All files were then transferred to a separate PC for digitising and calculation of 3D coordinates using the Ariel Performance Analysis System (APAS) software. The first step of this process was to use the APAS 'Trim' function to obtain one complete SC. The start and end points of the SC were defined as the video field at which the 3rd metacarpal tip of the hand entered the water. The hand selected for analysis was based on the first to enter the calibrated space with the whole body also in view. The time codes displayed on the left hand corner of each camera view was used as a reference to ensure accurate trimming. Trimming was completed for all six camera views. Before proceeding, all six camera views, per SC, were checked to ensure that the data sets were in exact temporal correspondence.

The APAS 'Digitise' function was used to create two sequence files, one for the above and one for the below water camera views. Creating sequence files is likened to that of creating a template, in which one determines the landmarks to be identified and specifies the order in which this is completed. Embedded in the sequence file was also the number and position of calibration points of the frame (20 points were selected in this study). Once the sequence files were completed, they were subsequently used as a reference for all files during the digitising process. The specified reference points were manually digitised in the following order: fixed point, vertex of the head, left finger, left wrist, left elbow, left shoulder, left hip, left ankle, left 5th metatarsophalangeal joint, left 1st interphalangeal joint, and then the corresponding points for the right side. This was repeated for each frame within the SC. A key feature in the APAS software is, if a reference point is not visible in a particular frame, APAS allows one to 'skip' that point, rather than estimating the point on the screen. On completion of each fully digitised SC, the calibration points corresponding to the camera view previously digitised were then processed. It should be highlighted that no underwater calibration point was digitised from the above water view, and vice versa. As a result, no errors were introduced due to refraction phenomena in the different mediums (air to water) during the digitising process.

The APAS 'Transform' function was used for each SC and for each of the above and below water views. The transform function is based on calculations from the DLT method. This applied the DLT equations to the digitised data to produce the 3D coordinate data for the above and below water views.

The final component of the APAS data processing procedure was to use the APAS 'Display' function which produces columns of the raw displacement data (x,y,z) for all digitised landmarks. Above and below water data were presented in separate files.

The output files from the ‘Display’ function were saved as Microsoft Excel files. The above and below water files were then combined into one single excel file representing continuous coordinates throughout the SC. These files were then saved as ‘text’ files, as a prerequisite for inputting the data into a MATLAB program for calculation of the variables.

3.6.3. Calculation of Variables

A MATLAB program developed by Sanders (2007) was used for all variable calculations in this study. The raw displacement and anthropometric data were input into the MATLAB program as ‘text’ files, as previously detailed. This process was completed for each SC (12 stroke cycles per swimmer) and for each swimmer (n=15).

A Fourier transform retaining 6 harmonics was used to smooth the raw data. The use of the Fourier series transform is regarded as highly appropriate when analysing periodic data, whereby the movement being examined displays a cyclical pattern, such as in swimming (Bartlett, 1997). It operates by removing noise as the series of sinusoidal waves above a ‘cut-off’ specified frequency. Bartlett (1997) recommended a cut-off frequency between 4-8Hz for human movement. However, Antonsson and Mann (1985) suggested that a lower cut-off frequency may be preferable for swimming. In this study, the retention of 6 harmonics corresponded to a frequency cut-off between 4 and 7Hz depending on the duration of the swimming cycle.

Following the calculation of variables in the MATLAB program, all output data were presented as 101 points. These points represented the SC as a percentage, expressed by a 0 to 100 range of percent points. This controlled for the duration of cycles enabling comparisons between and within swimmers using a common base on the abscissa of the graphs. Nevertheless, real time values corresponding to each percent point were also output.

3.6.3.1. Average velocity, stroke frequency, stroke length and stroke index

The average horizontal swimming velocity ($m \cdot s^{-1}$) for each swimmer was calculated by dividing the swimmer's mean COM horizontal displacement by the time it took to complete one SC. Stroke frequency ($cycles \cdot min^{-1}$) was the inverse of the time (seconds) it took to complete one SC which was then multiplied by 60. Stroke length (m) was the horizontal displacement of the COM during SC by one (representing one complete SC). The stroke index ($m^2.cycles \cdot min^{-1}$) was quantified as the product of the stroke length and swim velocity.

These variables were quantified to illustrate the fundamental parameters of swim performance and display how these were influenced by the swimming velocity.

3.6.3.2. Displacement Stroke Pathway of the Hand

The vertical motion of the arm pathway was analysed by calculating the maximum displacement (m) of the finger throughout the underwater phase of the SC in the vertical plane aligned in the direction of intended motion. Maxima, minima and range of motion were determined, as well as the times corresponding to the instants of attainment of the maxima and minima as both percent points of the SC and as real time relative to the commencement of the SC**.**

The lateral motion of the upper limb segment during the underwater phase was calculated as the absolute maximum and range of the finger, wrist and elbow displacement (m) in the vertical plane perpendicular to the intended motion. The lateral displacement data were expressed with respect to the swimmer's COM so that the hand movement was depicted as moving past a stationary body, i.e. the swimmer, making the data more interpretable. The time corresponding to the maximum lateral displacement of the finger was also calculated and expressed as a percentage of the overall SC. The lateral displacement calculations provided information on the extent of the lateral 'sweeping' motion of the arm during the SC.

3.6.3.3. Shoulder and Hip Roll

Shoulder roll angle during the SC was determined as the angle between the unit vector of the line joining the shoulders, projected onto the YZ plane (i.e. the plane perpendicular to the swimming direction) and the horizontal. Computationally, this is

$$\operatorname{atan}(S_z/S_y)$$

Where S_z and S_y are the z and y components of the shoulder unit vector.

The hip roll angle was calculated in a similar manner as the shoulder roll.

$$\operatorname{atan}(H_z/H_y)$$

Where H_z and H_y are the z and y components of the hip unit vector.

The maximum shoulder and hip roll angles (degrees) were calculated for each side per SC. Rolling to the left occurred when the shoulder/hip joint of the left side was higher than that of the right side, and vice versa. The time corresponding to the peak shoulder/hip roll per side was also measured and expressed as a percentage of the SC. Additionally the range of the shoulder and hip roll angle was also quantified for each SC. The shoulder and hip roll data provided information with respect to the magnitude of the shoulder and hip roll during sprint and distance events.

3.6.3.4. Elbow Angle

To calculate the elbow angle the following equation was utilised:

$$\theta = \operatorname{acos}(a \cdot b/|a||b|)$$

Where, $|a||b|$ is the length of vector a (Figure 3.17) multiplied by the length of vector b and $a \cdot b$ is the dot product of vectors a and b.

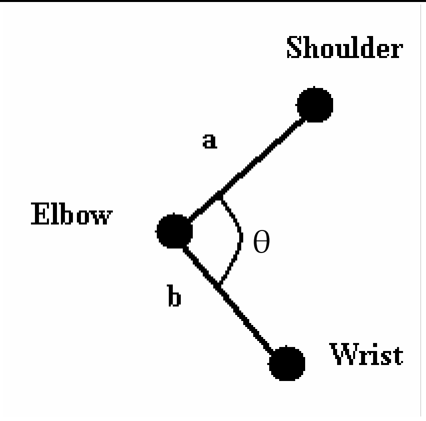


Figure 3.17: Calculation of the elbow angle

The elbow angle was quantified at five different instants within the underwater SC corresponding to the transitions between the stroke phases. Namely, at the moment:

1. The 3rd finger begins to move backwards following entering the water (1ST back). Point ‘X_2’ in Figure 3.18.
2. The 3rd finger is vertically aligned to the shoulder joint (shoulder x). Point ‘X_3’ in Figure 3.18.
3. The 3rd finger stops moving backwards (end back) Point ‘X_4’ in Figure 3.18.
4. When the 3rd finger exits the water (hand exit). Point ‘X_6’ in Figure 3.19.
5. The same finger breaks the water surface (recovery). Point ‘X_5’ in Figure 3.18.

Moreover, it should be stated that the ‘1st back’ elbow angle represents the ‘catch’ event. This position is regarded as one of the fundamental aspects of all swimming strokes, due to propulsion said to commence at, or soon after, this moment.

Additionally, with reference to the above instants, the elbow angle range during the pull and push phases was calculated:

1. Range 1 = Elbow angle at instant ‘1st back’ - Elbow angle at instant ‘shoulder x’.
2. Range 2 = Elbow angle at instant ‘end back’ - Elbow angle at instant ‘shoulder x’.

The elbow angle calculations provided an indication of this parameter's behaviour, in terms of quantity and change, during the different underwater stroke phases.

3.6.3.5. Time Spent in Each of the Stroke Phases

Quantifying phases of a SC is common in swim research and performance for the purpose of analysis and skill development respectively. In this study, four separate phases; Entry, Pull, Push and Recovery were identified. Each phase, within every SC, was determined by the analysis of the swimmer's horizontal (x) and vertical displacement (y) of the 3rd finger and noting the time corresponding to these displacements. The phases were defined as follows, and graphically illustrated in Figures 3.18 and 3.19:

Entry 'X_1-X_2' (Figure 3.18): The time at which the finger breaks the water surface on entry to the time of the first backward movement of the finger.

Pull 'X_2-X_3' (Figure 3.18): Time of first backward movement of the finger, until the time the finger is vertically 'in-line' with the shoulder joint.

Push 'X_3-X_4' (Figure 3.18): Time of the finger inline with the shoulder joint to the time of the last backward movement of the finger.

Recovery 'X_4-X_5' (Figure 3.18): Time of last backward movement of the finger, until the time the same finger enters the water again.

The time, expressed as a percentage of the SC, at which the hand exits the water was also quantified. The duration of different phases, when compared between sprint and distance events, is used to provide information on how swimmers distribute their time within the SC.

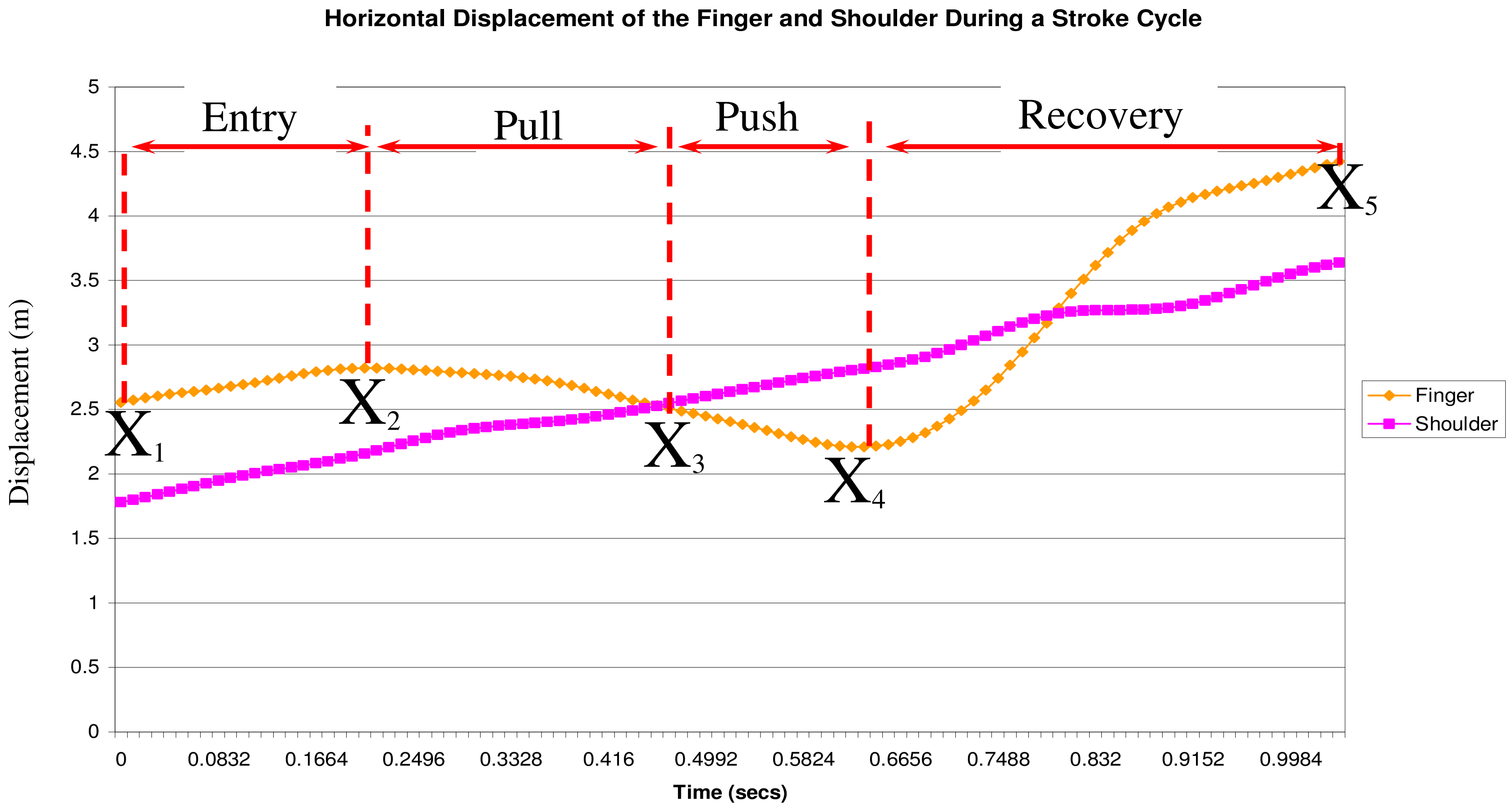


Figure 3.18: X1= finger entry, X2= beginning of finger moving backward, X3= finger inline with the shoulder, X4= end of backwards movement, X5= finger entry again.

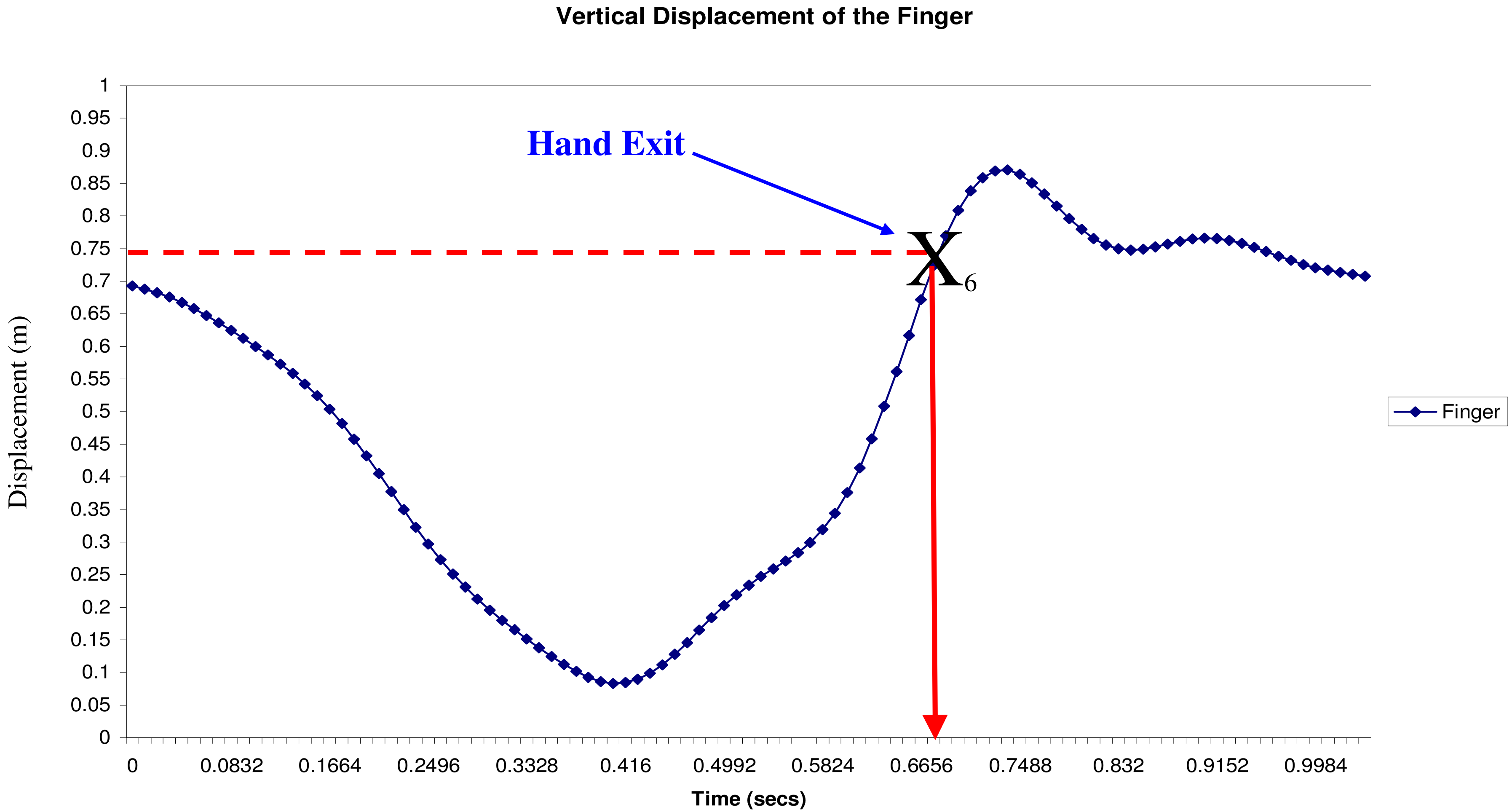


Figure 3.19: X6 = hand exiting the water.

3.6.3.6. Kicking Vertical Range of Motion

The flutter kick consists of the legs alternately executing an upbeat and downbeat action in an antagonistic manner. An upbeat and downbeat kick is defined as the end of the upbeat and downbeats of the foot respectively during a kick cycle (Figure 3.20 for illustration of events). In swim research and performance, the leg action is measured by quantifying the number of beats (up and down) within one complete SC. For example, many researchers have recommended that sprinters should utilise a six beat kick action per SC (three downward beats per arm stroke), whereas distance and middle distance swimmers are advised to use fewer beats per cycle, such as a two beat kick (one downward beat for each arm stroke) or a four beat kick action (two downward beats for each arm stroke) (Counsilman, 1977; Costill et al., 1992).

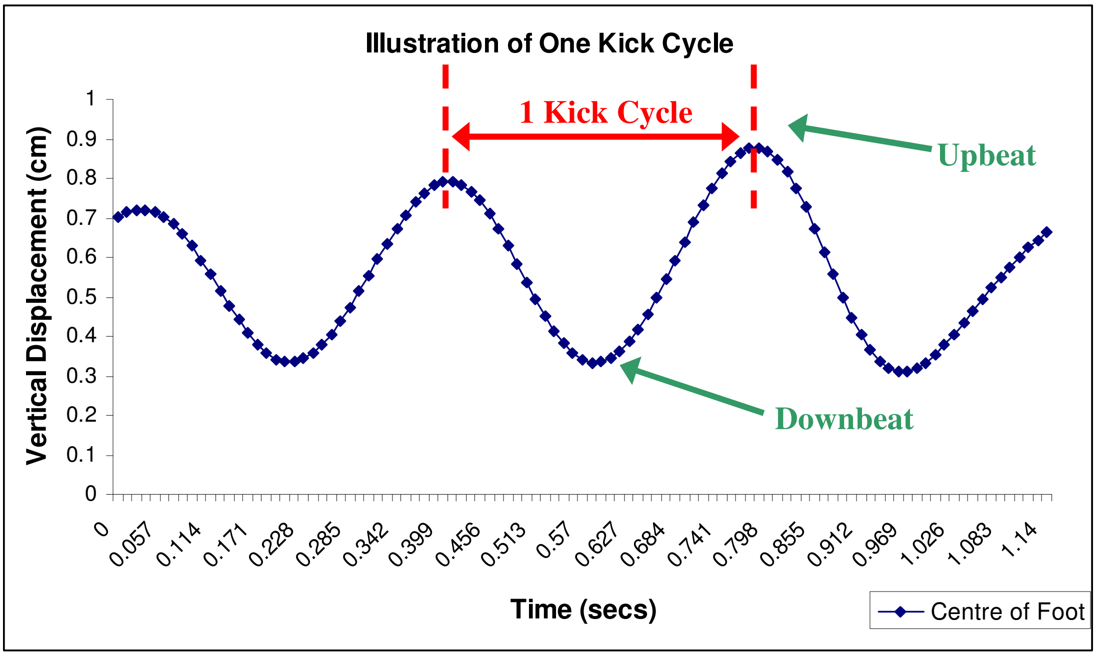


Figure 3.20: Vertical displacement of the foot during one complete stroke cycle. Diagram illustrates the upbeat and downbeat during one kick cycle.

The vertical displacement (cm) of this parameter in the 'y' plane was represented by quantifying the centre of the foot:

$$= \frac{\text{vertical displacement of ankle + vertical displacement of the big toe}}{2}$$

The centre of the foot displacement was calculated for all 101 points per SC, and for all stroke cycles per swimmer. The displacement of the foot was graphed for both feet so that the beats of the kick were easily identifiable.

Each upbeat and downbeat action of the kick was quantified as the maximum and minimum vertical displacement of the foot respectively. This was performed for each foot within each SC. The vertical displacement range was calculated between an up and downbeat portion, and vice versa. These measurements provided information with respect to the number of upbeat and downbeat kicks within a SC, and also the depth range of the foot when swimming at a sprint and distance pace.

3.6.3.7. COM Horizontal Velocity Pattern

The COM displacement (cm) was determined by summing the moments of the segment centres of mass about the X, Y, and Z reference axes. The velocity of the COM ($m \cdot sec^{-1}$) was obtained by differentiating the COM displacement data using the first central difference formula. The horizontal maximum and minimum instantaneous COM velocities, in addition to the range between these two parameters, were calculated for each underwater SC.

Analysis of the horizontal COM velocity profile (V_{COMHor}) provided information with regard to velocity fluctuations when swimming at different speeds.

3.6.3.8. COM Horizontal Acceleration

COM acceleration (acc_{COM}) was obtained by differentiating the COM displacement data using the second central difference formula.

3.6.3.9. COM Net Force

The COM net force ($force_{COM}$) was calculated as the product of COM acceleration and the mass of the swimmer. The maxima and minima were determined, as well as the times corresponding to these instants as both percent points of the SC and as real time relative to the commencement of the SC. These calculations provided information on the resultant magnitude of the sum of propulsive and resistive forces throughout the SC.

3.7. Reliability

To assess the reliability of the investigator's digitising technique on all of the aforementioned kinematic variables, one single SC was digitised five times for all six camera views. For each of the kinematic and kinetic variables, the standard deviation and 95% confidence interval (CI) of the five repeat digitisations were used as an indication of the reliability.

3.8. Statistical Analysis

The processed data were analysed using the Statistical Package for Social Sciences (SPSS) version 14.0. Descriptive statistics including the mean, and standard deviations were calculated for all the data in Microsoft Office Excel 2003 software.

The data were pre-analysed to assess for any learning or fatigue affects within the trials. A single factor ANOVA, with the lap number as the factor, was used to evaluate whether any of the laps differed significantly in magnitude relative to each other. This was repeated for each kinematic and kinetic variable. Within the four 25m sprints, trial number one was different from the other three trials in the majority of kinematic and kinetic variables. Within the 400m swim, lap numbers 1, 4, 7 and 8 where consistently different from laps 2, 5 and 6. Based on this finding, the mean of the three trials per swim condition which did not differ from each other (sprinting: number 2, 3, and 4; distance swimming: 2, 5 and 6) were used for statistical analysis.

A two factor mixed design ANOVA with an independent factor (factor A: group), being a sprint specialisation group and a distance specialisation group, and a repeated measures factor (factor B: pace), being sprint and distance pace, was used to analyse the data based on the fact that each swimmer swims both conditions of the speed factor. The differences between groups and paces as well as the interactions between these, were tested with the confidence level of $p < 0.05$ accepted as significant. Post hoc analysis was also performed and a Bonferroni adjustment made for multiple comparisons ($p < 0.0125$).

In statistical analysis using a repeated measures ANOVA the criterion of sphericity, that is, homogeneity of variance and homogeneity of covariance must be met. Homogeneity of covariance means that the relationships, or correlations, on the dependent variable among all of the three or more repeated measures are equal. However, when only two repeated measures are employed, such as sprint and distance swimming, this assumption is not applicable, because there are too few points to establish a correlation coefficient.

To compliment the above, a 95% CI of the true mean was quantified for each variable. The upper and lower CI boundaries were presented on the graphs instead of the standard error bars to indicate the range in which the true value of the variable fell 95% of the time. All CI calculations were quantified using Microsoft Office Excel 2003 software, using the formula:

$$CI = X \pm (z \times SE)$$

Whereby X is the mean, z is the z-score for the particular confidence level of interest and SE is the standard error. Since this study required a 95% confidence level, the value of z would be 1.96. The SE is calculated as:

$$SE = SD / \sqrt{n}$$

Where SD is the standard deviation and n is the number of number of cases/subjects.

The effect size (d) for each variable was also calculated to measure the magnitude of change between swimming at a sprint and distance pace (within groups) and to assess the magnitude of change between sprint and distance swimmers (within paces). The general effect size formula is given as:

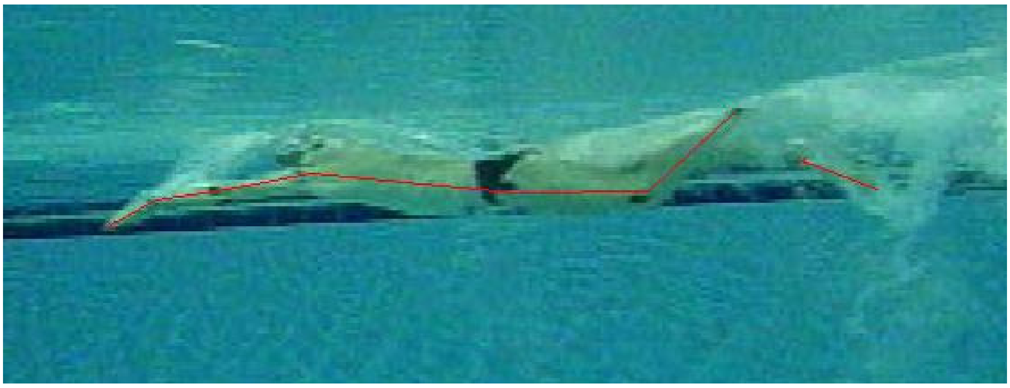
$$\text{Effect Size} = \text{Mean of dataset}_1 - \text{Mean of dataset}_2 / \text{Standard Deviation}$$

This formula presents two problems. Firstly, the effect size quantifies the difference between two datasets, but it is not obvious which dataset should be subtracted from the other, making it important to quote which order the calculations are performed. In this study, calculating the effect size between paces (within the SG and DG) was performed by subtracting the mean of the distance pace variable from the mean of the sprint pace variable. When calculating the effect size between groups (within the sprint and distance paces), the mean of the DG variable was subtracted from the mean of the SG variable. Secondly, it is almost never known which standard deviation to use. It is therefore recommended that a ‘pooled’ standard deviation (s_p), which is the average of the standard deviations of both datasets (Coe, 2002):

$$s_p = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}}$$

Where n_1 and s_1 are the number of cases and standard deviation within the first dataset; n_2 and s_2 are the number of cases and standard deviation within the second dataset. The criteria for interpreting the absolute effect size, was based on Cohen’s (1992) suggestion that effect sizes of 0.2 are small, 0.5 are moderate and 0.8 are large. These values enable us to compare effect size results to known benchmarks.

Chapter Four: Results



In this section, the results of the race parameters in addition to kinematic and kinetic variables are presented. Tables and graphs are used to illustrate the results and to highlight the differences between sprint and distance pace for both groups.

4.1. Reliability of Calculated Variables

Table 4.1 presents the results from the reliability calculations, based on the same swim trial digitised five times. The 95% confidence intervals show the range in which the true value of that particular variable fell 95% of the time. The standard deviation (SD) values were considered small and acceptable for most variables. However, the results for some variables need to be interpreted cautiously, namely: time to max V_{COMHor}, time to max acc_{COM}, time to min acc_{COM}, max $force_{COM}$, time to max $force_{COM}$, min $force_{COM}$, maximum right hip roll angle, elbow angle at hand exit and re-entry which had higher variability in terms of SD magnitude.

Variable	*Mean*	*Standard Deviation*	*95% Confidence Intervals*	
			Lower	*Upper*
SL (m)	2.63	0.01	2.62	2.64
SF (cycles·min^{-1})	31.0	0.14	30.87	31.11
SI (m^{2}·cycles^{-1}·s^{-1})	3.57	0.02	3.55	3.59
V_{av} (m·s^{-1})	1.36	0.003	1.35	1.36
Max finger vertical depth (m)	0.69	0.012	0.68	0.70
Time to max finger depth (% SC)	60.2	0.45	59.81	60.59
Max finger lateral displacement (m)	0.60	0.01	0.59	0.61
Time to max lateral displacement of finger (% SC)	54.2	0.45	53.81	54.59
Range of finger lateral displacement (m)	0.61	0.02	0.59	0.63
Range of wrist lateral displacement (m)	0.49	0.02	0.47	0.51
Range of elbow lateral displacement (m)	0.36	0.01	0.35	0.37
Max shoulder roll- right (°)	47.4	1.61	45.99	48.81
Time to right shoulder roll (% SC)	37.4	0.55	36.92	37.88
Max hip roll- right (°)	35.2	4.92	30.90	39.52
Time to right hip roll (% SC)	43.2	1.48	41.90	44.50
Max shoulder roll- left (°)	78.7	2.87	76.20	81.24

Time to max left shoulder roll (% SC)	88.4	0.55	87.92	88.88
Max hip roll- left (°)	49.9	4.72	45.73	54.01
Time to max left hip roll (% SC)	97.3	0.50	96.81	97.69
Elbow angle at 1st back (°)	170.0	4.32	166.19	173.77
Elbow angle at 'shoulder x' (°)	101.2	2.02	99.44	102.98
Elbow angle at end back (°)	117.1	3.82	113.71	120.41
Elbow angle at hand exit (°)	52.3	4.80	48.09	56.51
Elbow angle at re-entry (°)	147.8	5.96	142.58	153.02
Elbow angle range for pull phase (°)	68.8	4.15	65.13	72.41
Elbow angle range for push phase (°)	15.9	2.85	13.35	18.35
Time spent in entry phase (% SC)	48.6	0.55	48.12	49.08
Time spent in pull phase (% SC)	15.2	0.45	14.81	15.59
Time spent in push phase (% SC)	11.6	0.55	11.12	12.08
Time spent in recovery phase (% SC)	24.6	0.55	24.12	25.08
Time at hand exit (% SC)	85.4	0.55	84.92	85.88
Average left foot vertical displacement range (m)	0.19	0.002	0.185	0.189
Average right foot vertical displacement range (m)	0.086	0.004	0.082	0.089
Sum av foot vertical displacement (m)	0.136	0.003	0.133	0.139
Av V_{COMHor} (m·s^{-1})	1.36	0.003	1.36	1.36
MaxV_{COMHor} (m·s^{-1})	1.46	0.017	1.45	1.47
Time to MaxV_{COMHor} (% SC)	20.00	21.31	1.32	38.68
MinV_{COMHor} (m·s^{-1})	1.22	0.032	1.19	1.25
Time to MaxV_{COMHor} (% SC)	48.20	1.64	46.76	49.64
Max acc$_{COM}$ (m·s^{-2})	1.37	0.29	1.12	1.62
Time at max acc$_{COM}$ (% SC)	34.20	28.08	9.59	58.81
Min acc$_{COM}$ (m·s^{-2})	-1.10	0.26	-1.33	-0.87
Time at min acc$_{COM}$ (% SC)	45.20	25.6	22.76	67.64
Max force$_{COM}$ (N)	113.93	23.90	92.98	134.88
Time at max force$_{COM}$ (% SC)	34.20	28.08	9.59	58.81
Min force$_{COM}$ (N)	-91.78	21.76	-110.85	-75.71

Table 4.1 Reliability of all variables calculated in this study.

4.2. Race Parameters

Table 4.2 presents all the effect sizes for the race parameter variables.

Parameter	*Effect Size SG*	*Effect Size DG*	*Effect Size Sprint*	*Effect Size Distance*
V_{av}	6.14	6.00	0.17	-1.64
SL	-0.91	-1.43	0.24	0.20
SF	2.89	3.80	-0.17	-0.55
SI	1.20	0.81	0.27	-0.36

Table 4.2: Effect size values for V_{av}, SL, SF and SI. The effect size between paces within the SG and DG are presented on the left side columns. The effect size between groups within the sprint and distance paces are presented on the right side columns.

4.2.1. Average Swimming Speed

It is clear from Figure 4.1 that both groups achieved a greater V_{av} when swimming at sprint than distance pace. The difference between the two paces (0.40 $m \cdot s^{-1}$ and 0.30 $m \cdot s^{-1}$ for SG and DG respectively) was significant ($p< 0.001$), which is further supported by the large effect size of both these variables (Table 4.2). Both the groups and the pace-group interaction approached significance ($p= 0.071$). Post hoc analysis showed that the difference in V_{av} between the DG and SG approached significance at the distance pace trials ($p= 0.015$), with the DG faster than the SG when distance swimming but not when sprinting. Moreover, Table 4.2 presents that there was a large effect size between the groups at distance pace, supporting the post hoc analysis.

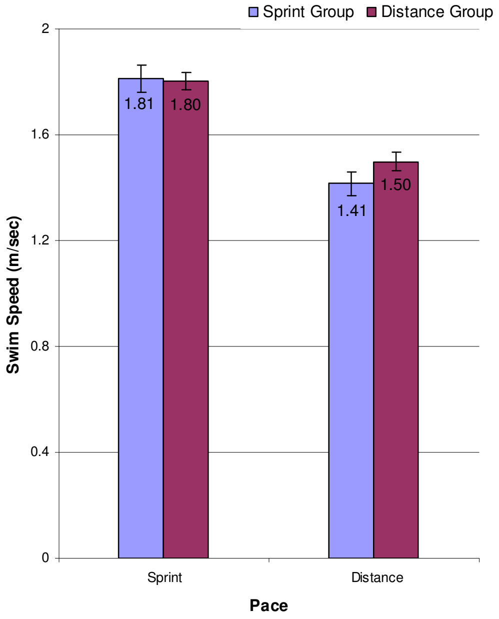


Figure 4.1: V_{av} - SG vs. DG, at both sprint and distance pace. Mean swimming speed (m/sec) values are indicated. Error bars represent 95% confidence interval of the true mean.

4.2.2. Stroke Length

The difference in SL between sprint and distance pace was significant ($p< 0.001$). The SL effect size was also found as large for both groups (Table 4.2). Figure 4.2 shows that SL was greater at distance pace (2.24 ± 0.32m- SG and 2.19 ± 0.18m- DG) than sprint pace (2.00 ± 0.19m- SG and 1.96 ± 0.14m- DG). Post hoc analysis revealed that the DG adjusted SL significantly between the paces ($p< 0.0125$), whereas the SG approached significance ($p= 0.030$). There was no significant difference between groups ($p= 0.672$) nor a significant pace-group interaction ($p= 0.944$), which is supported by the small effect size values in Table 4.2.

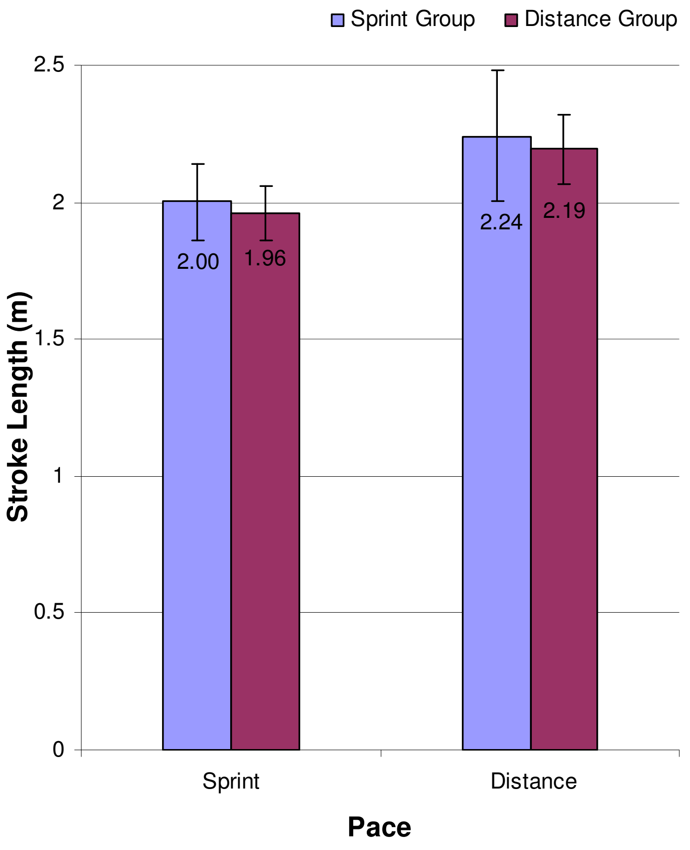


Figure 4.2: SL- SG vs. DG at both sprint and distance pace. Mean stroke length (m) values are indicated. Error bars represent 95% confidence interval of the true mean.

4.2.3. Stroke Frequency

SF was significantly different between paces for both groups ($p<0.001$) (Figure 4.3), which is supported by the large effect sizes for the SG (d= 2.89) and the DG (d= 3.80) between paces. The SF when sprinting (54.64 ± 5.08 cycles·min^{-1}- SG and 55.38 ± 3.73 cycles·min^{-1}- DG) was greater by 16.05 cycles·min^{-1} (SG) and 14.12 cycles·min^{-1} (DG) than distance pace (38.59 ± 6.00 cycles·min^{-1}- SG and 41.26 ± 3.70 cycles·min^{-1}- DG). There was no significant difference between the groups (p= 0.433) nor a significant pace-group interaction (p= 0.431), despite a moderate effect size between the groups at distance pace (d= -0.55).

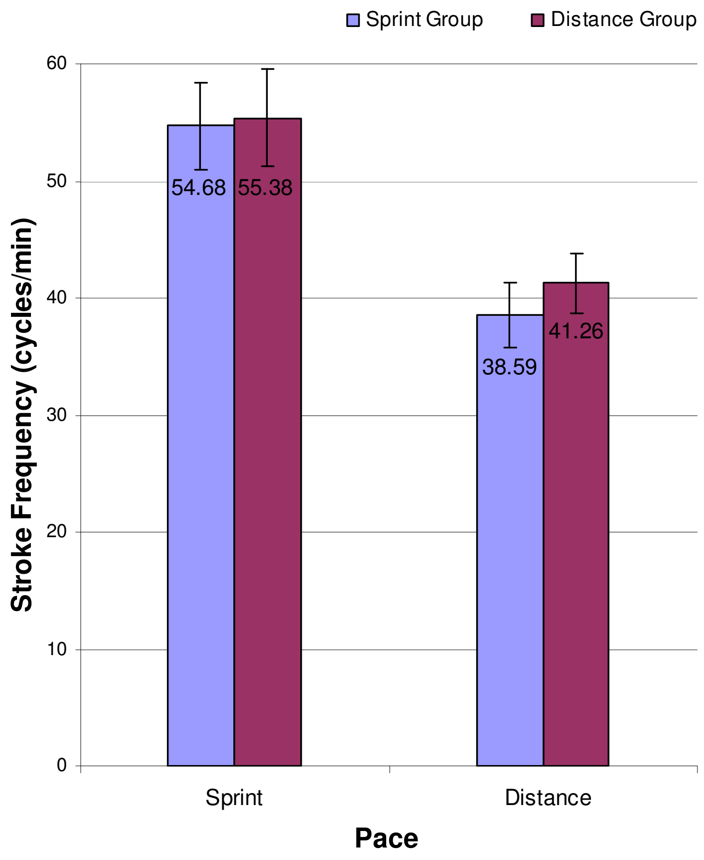


Figure 4.3: SF- SG vs. DG at sprint and distance pace. Mean stroke frequency (cycles/min) values are indicated. Error bars represent 95% confidence interval of the true mean.

4.2.4. Stroke Index

SI was significantly greater at sprint than distance pace ($p < 0.001$) by 0.47 $m^2 \cdot cycles^{-1} \cdot s^{-1}$ and 0.25 $m^2 \cdot cycles^{-1} \cdot s^{-1}$ respectively for SG and DG (Figure 4.4). Both groups showed a large effect between paces (Table 4.2). Moreover, post hoc analysis revealed a significant difference between paces within the SG ($p < 0.0125$) but not within the DG ($p = 0.0232$). There was no significant difference between groups ($p = 0.924$) nor a significant pace-group interaction ($p = 0.122$).

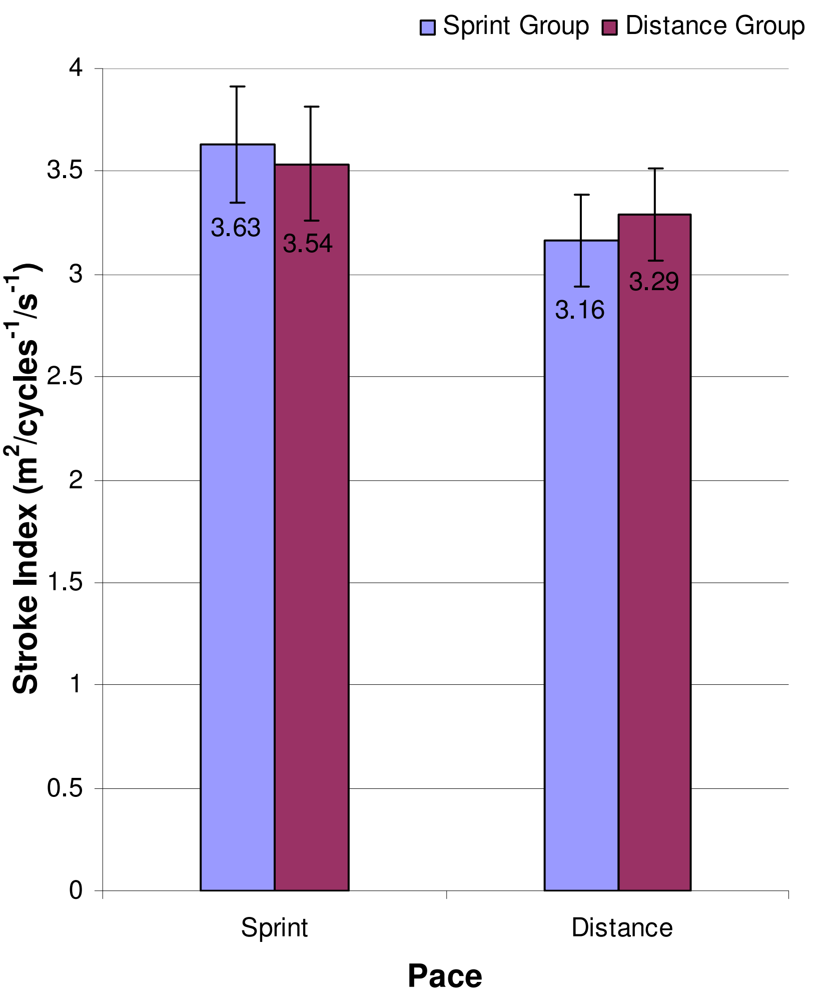


Figure 4.4: SI- SG vs. DG at sprint and distance pace. Mean stroke index ($m^2 \cdot cycles^{-1} \cdot s^{-1}$) values are indicated. Error bars represent 95% confidence interval of the true mean.

4.3. Kinematic Parameters

4.3.1. Arm Displacement

The vertical displacement of the arm was measured with respect to an external reference frame. The lateral displacement of the arm was quantified with respect to an internal reference frame with the COM as the origin and with its axes parallel to the external reference frame. Table 4.3 presents the effect sizes for the finger, wrist and elbow displacement data.

	Effect Size SG	*Effect Size DG*	*Effect Size Sprint*	*Effect Size Distance*
Max Vertical Finger	-0.01	-0.18	0.06	-0.08
Max Vertical Wrist	-0.04	-0.24	0.04	-0.10
Max Vertical Elbow	-0.03	-0.48	0.23	-0.11
Time to Max Vertical Finger	-1.46	-1.07	0.02	0.36
Max Lateral Finger	-0.07	-0.15	-0.05	-0.03
Max Lateral Wrist	-0.20	-0.06	-0.45	-0.14
Max Lateral Elbow	-0.15	-0.05	0.40	0.43
Time to Max Lateral Finger	-1.80	-0.17	-1.11	-0.03

Table 4.3: Effect size values for the vertical and lateral displacement of the finger, wrist and elbow for SG and DG. The effect size between paces within the SG and DG are presented on the left side columns. The effect size between groups within the sprint and distance paces are presented on the right side columns.

4.3.1.1. Finger Vertical Displacement

There was no significant difference in maximum vertical displacement of the finger between the paces (p= 0.755), or swim groups (p= 0.852) (Figure 4.5).

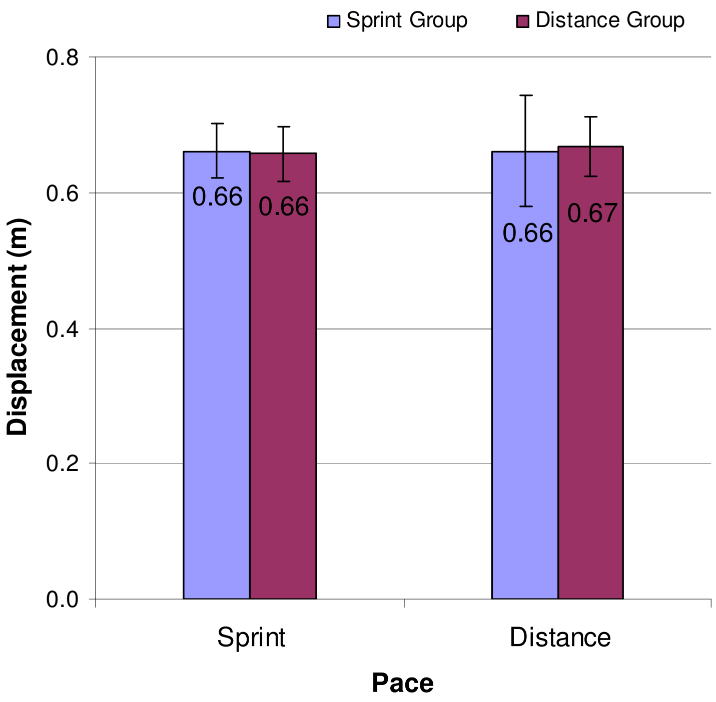


Figure 4.5: Maximum vertical displacement of the finger- SG vs. DG at sprint and distance pace. Mean displacement (m) values are indicated. Error bars represent 95% confidence interval of the true mean.

However, Figures 4.6 & 4.7 indicate that five participants made individual changes between paces with respect to maximum finger vertical displacement. Sprint participants 2, 3 and 4 changed the mean maximum finger depth by +0.10 m, -0.13 m and +0.06 m respectively, at sprint than distance pace (Figure 4.6). Distance participants 4 and 5 changed the mean maximum stroke depth by +0.03 m and -0.08 m (Figure 4.7) between sprint and distance pace. These results indicate that despite a lack of significant difference in group means between paces, some individuals changed this variable between paces. However, there was a lack of consistency among individuals in terms of the direction of change. Consequently, further investigation that includes a larger sample and a greater number of trials is warranted to examine individual and group effects more closely.

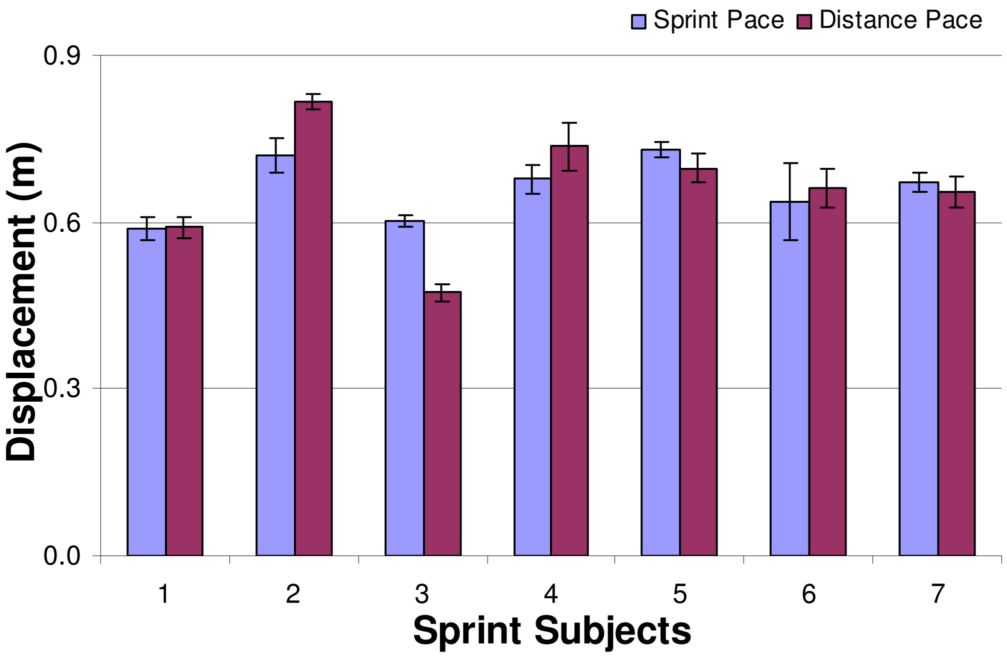


Figure 4.6: SG- maximum vertical displacement of the finger- sprint vs. distance pace. Participants 2 and 3 and 4 had differences in the means of this parameter between the two paces. The values presented are means of three trials per swim pace.

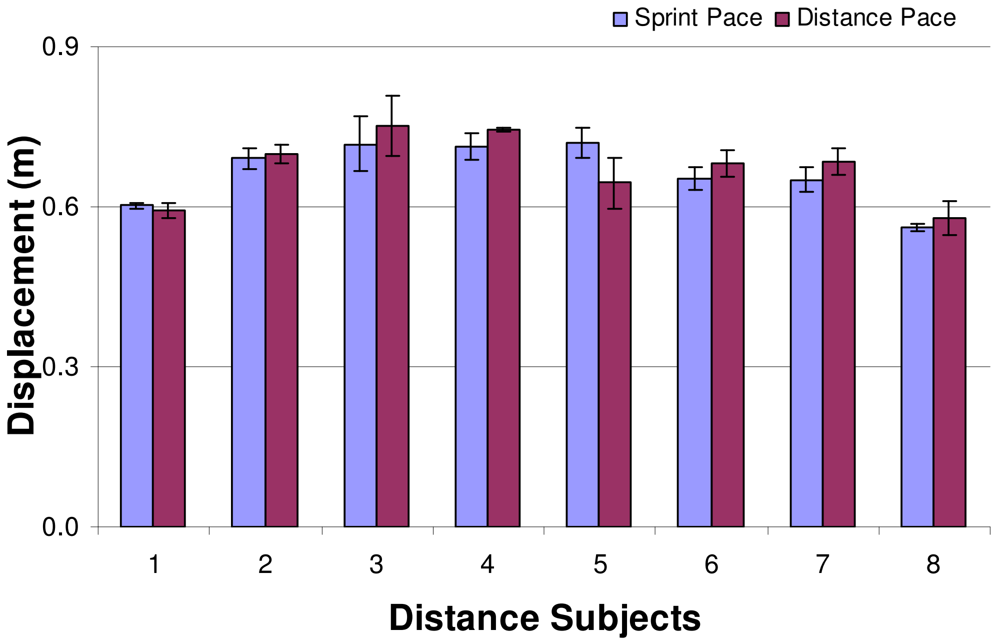


Figure 4.7: DG- maximum vertical displacement of the finger- sprint vs. distance pace. Participant 4 and 5 had differences in the means of this parameter between the two paces. The values presented are means of three trials per swim pace.

4.3.1.2. Time to Maximum Vertical Displacement of the Finger

The difference in time to maximum vertical displacement of the finger between paces was significant ($p < 0.001$), which is supported by the large effect size found for both groups across paces (Table 4.3). Figure 4.8 indicates that the time to reach the maximum finger vertical displacement is longer when distance swimming (51.52 ± 6.71%- SG and 48.79 ± 6.71%- DG) than sprinting (42.17 ± 5.61%-SG and 42.02 ± 5.86%-DG). Post hoc analysis revealed significant differences between paces within the DG ($p = 0.0107$), whereas the SG approached significance ($p = 0.035$). There was no significant difference between groups ($p = 0.389$) nor a significant pace-group interaction ($p = 0.851$).

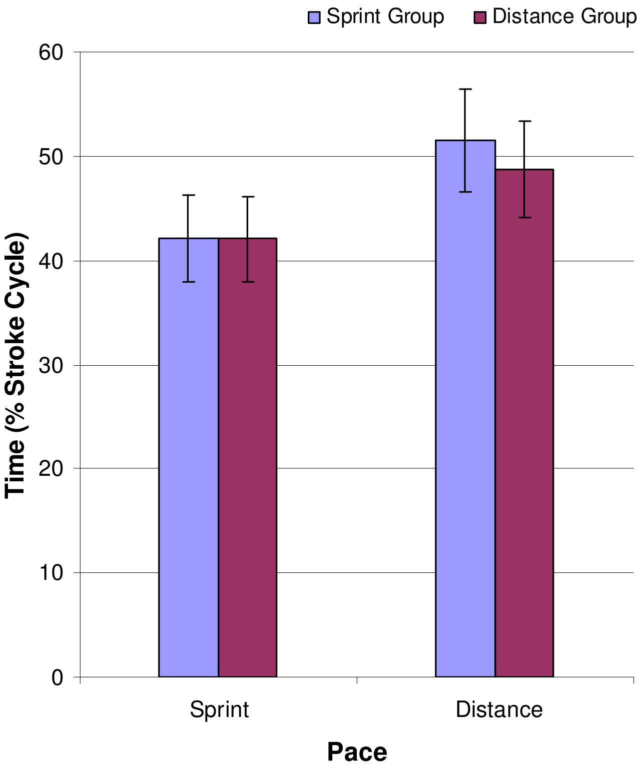


Figure 4.8: Time to maximum vertical displacement of the finger- SG vs. DG at sprint and distance pace. Error bars represent 95% confidence interval of the true mean.

4.3.1.3. Maximum Vertical Displacement of the Wrist and Elbow

There were no significant differences between paces for the maximum vertical displacement of the wrist ($p = 0.599$) or elbow ($p = 0.296$). Groups did not differ between maximum wrist ($p = 0.920$) or elbow ($p = 0.946$) vertical displacement (Figure

4.9). The pace-group interaction was not significantly different with respect to the wrist (p= 0.752) and elbow (p= 0.399).

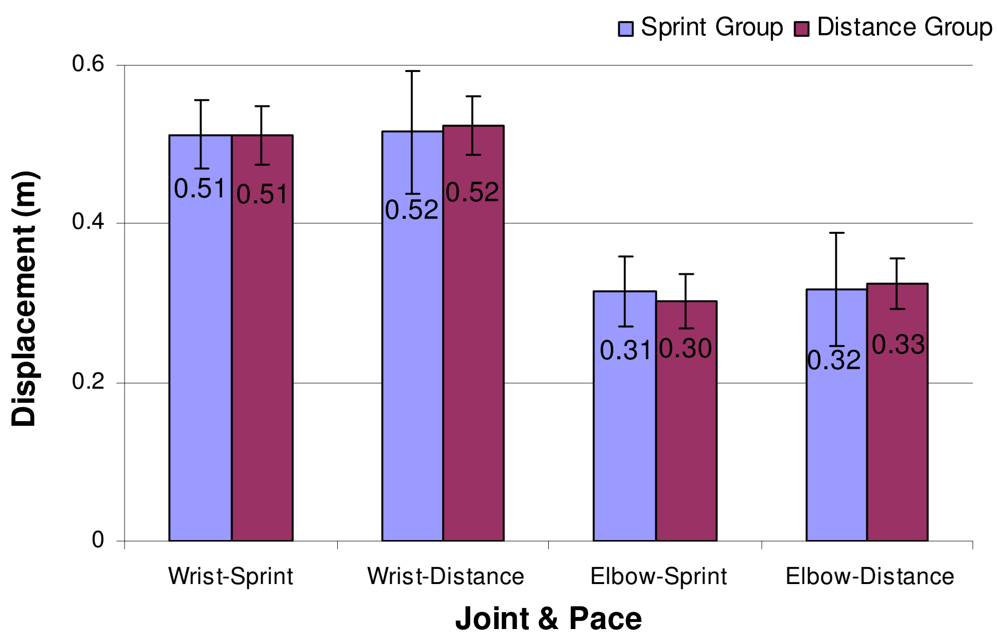


Figure 4.9: Maximum vertical displacement of the wrist and elbow- SG vs. DG at sprint and distance pace. Mean displacement (m) values are indicated. Error bars represent 95% confidence interval of the true mean.

Figures 4.10 and 4.11 illustrate data for two participants changed the maximum vertical displacement of both the wrist and elbow between paces. Sprint participant 2 (Figure 4.10) increased the mean vertical displacement of the finger, wrist and elbow by 0.10 m, 0.10 m and 0.09 m respectively when distance swimming relative to sprinting. Sprint participant 3 (Figure 4.11) decreased the mean vertical displacement of the finger, wrist and elbow by 0.13 m, 0.12 m and 0.08 m respectively when distance swimming relative to sprinting. These results indicate that despite a lack of significant difference in group means between paces, some individuals changed this variable between paces. Due to the lack of consistency among individuals in terms of direction of change, further investigation is warranted.

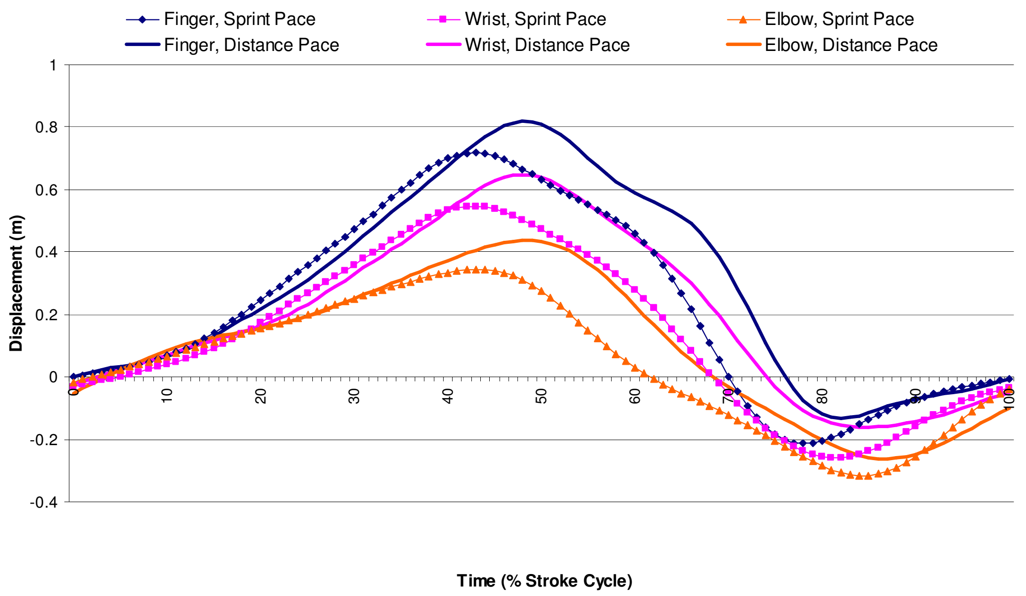


Figure 4.10: Vertical displacement of the finger, wrist and elbow for sprint participant 2- sprint vs. distance pace. These values are the mean of three trials per event.

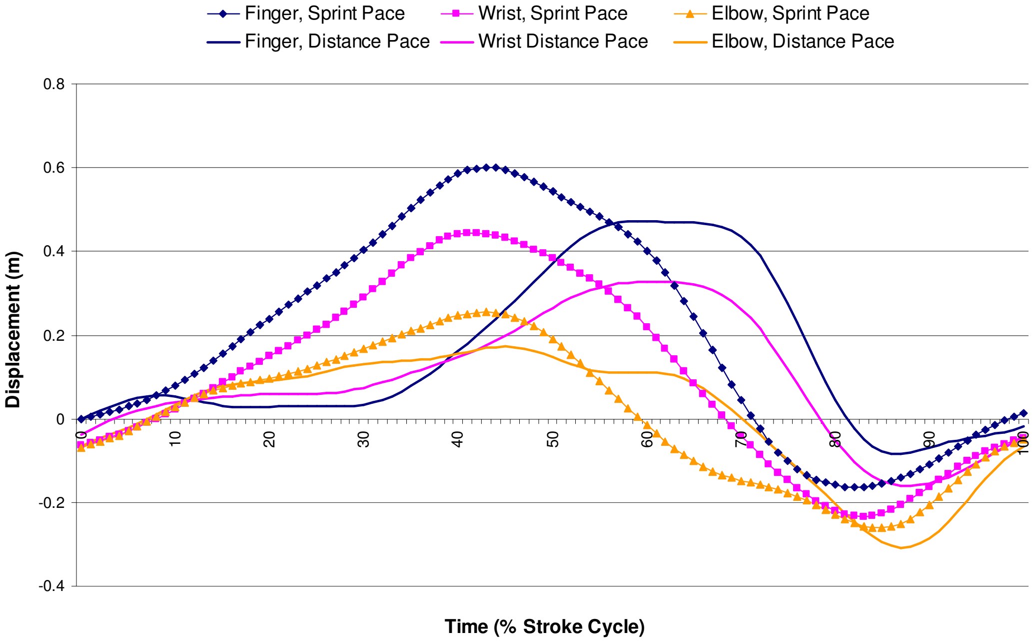


Figure 4.11: Vertical displacement of the finger, wrist and elbow for sprint participant 3- sprint vs. distance pace. These values are the mean of three trials per event.

4.3.1.4. Maximum Arm Lateral Displacement

There were no significant differences found for the maximum lateral displacement of the finger (p= 0.838), wrist (p= 0.587) or elbow (p= 0.635) between sprint and distance pace. There was no significant difference between groups with respect to maximum lateral displacement of the finger (p= 0.959), wrist (p= 0.569) or elbow (p= 0.406) (Figures 4.12 and 4.13). A small effect size was found between the groups within the sprint pace trials in relation to the maximum lateral displacement of the wrist (d= 0.45) and elbow (d= 0.40). The effect size for the elbow lateral displacement was also small between the groups within the distance pace trials (d= 0.43). Figures 4.12 and 4.13 indicate that all swimmers laterally displaced the finger relative to the COM, more than the wrist and elbow.

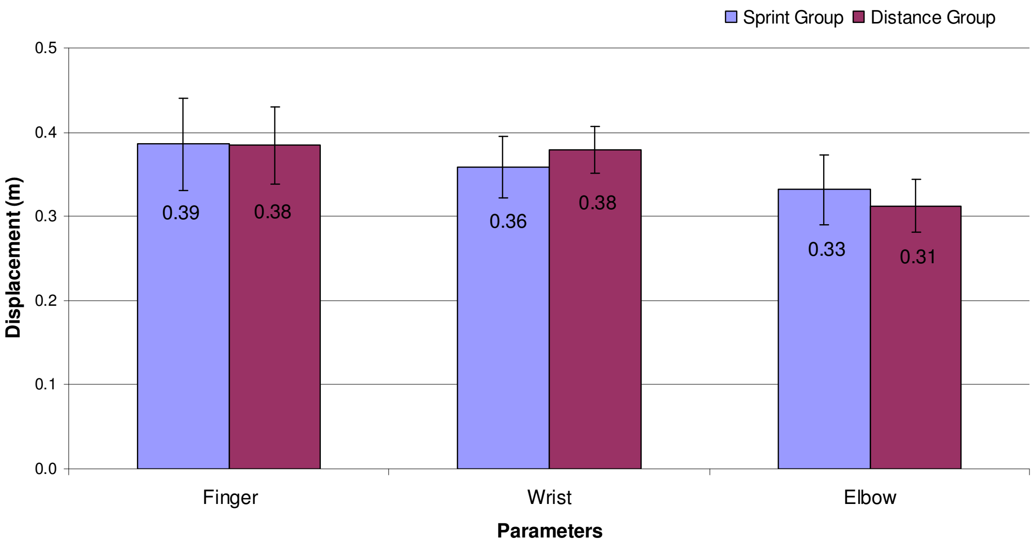


Figure 4.12: Max lateral displacement of the finger, wrist and elbow at sprint pace- SG vs. DG. Mean displacement (m) values are indicated. Error bars represent 95% confidence interval of the true mean.

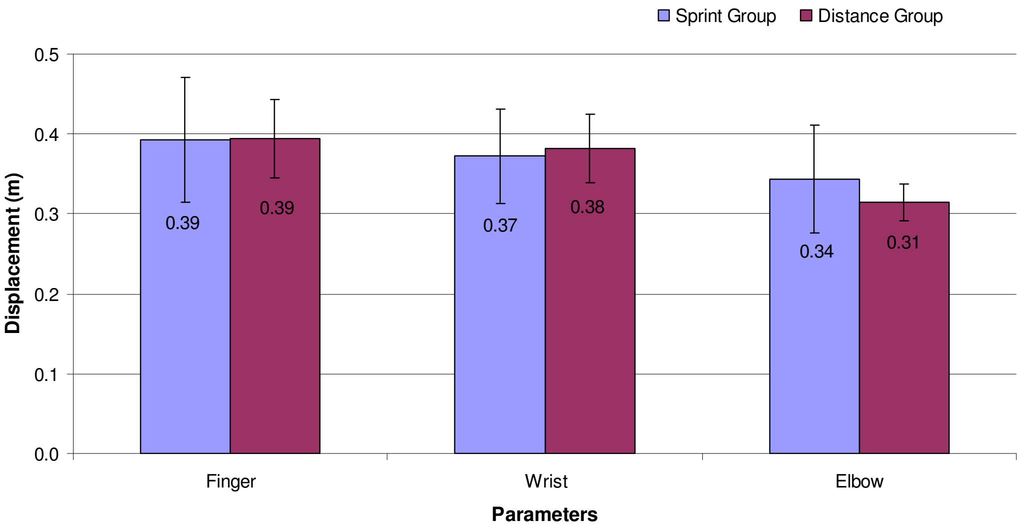


Figure 4.13: Maximum lateral displacement of the finger, wrist and elbow at distance pace- SG vs. DG. Mean displacement (m) values are indicated. Error bars represent 95% confidence interval of the true mean.

Figures 4.14 and 4.15 indicate that several individuals changed the magnitude of the maximum finger lateral displacement between paces. This is most apparent for distance participants 7 and 8 (Figure 4.15).

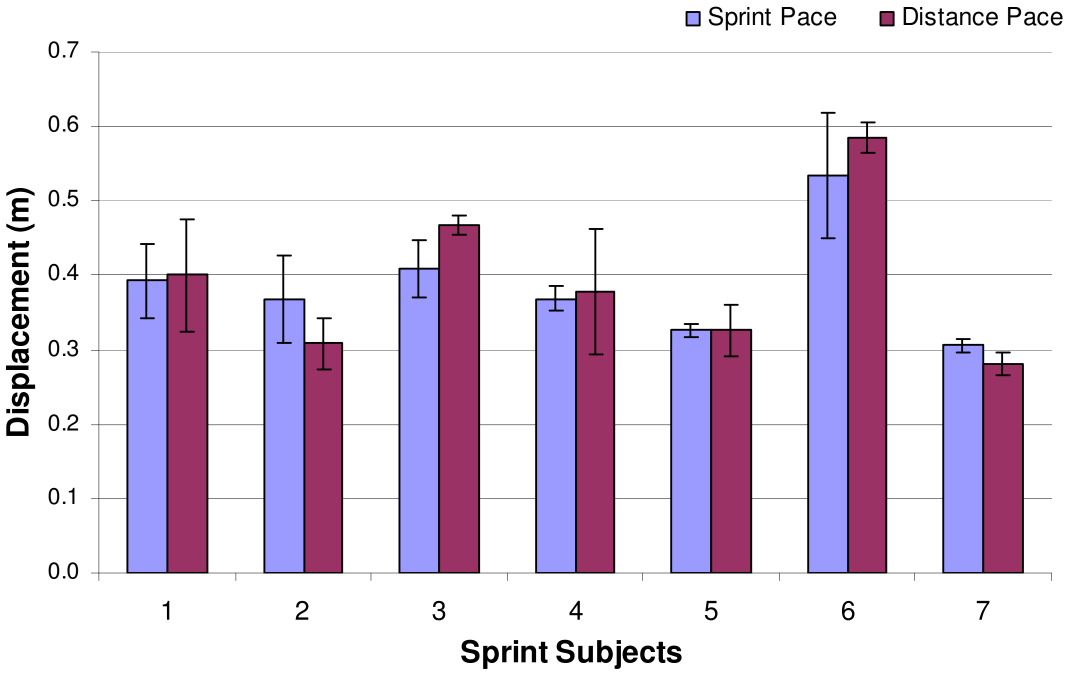


Figure 4.14: SG: maximum lateral displacement of the finger- sprint vs. distance pace.

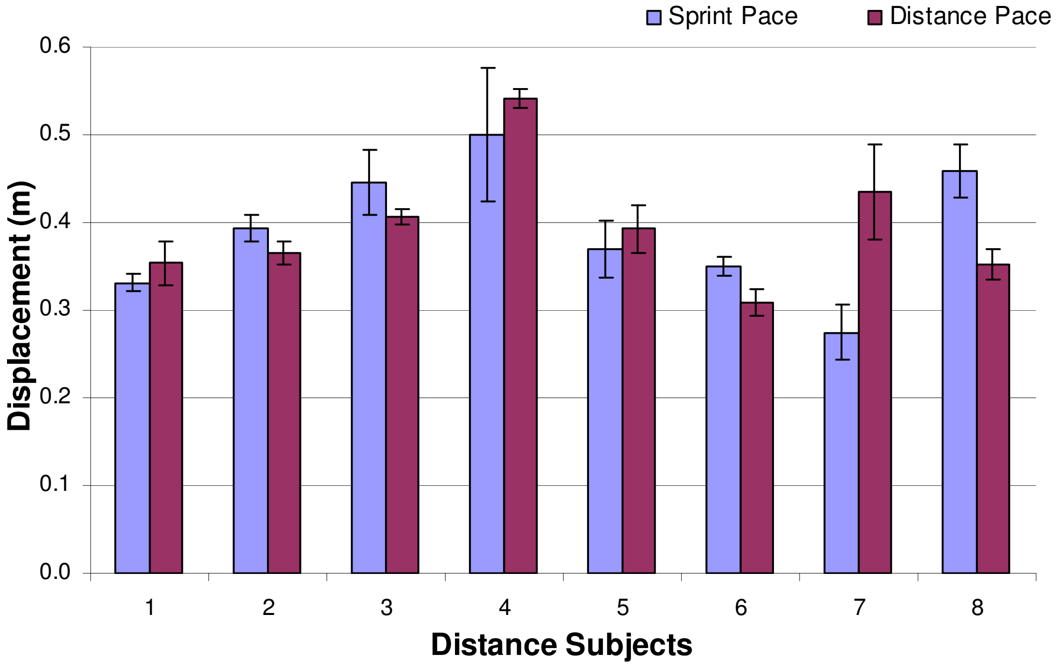


Figure 4.15: DG: maximum lateral displacement of the finger- sprint vs. distance pace.

The above adjustments made between paces had no directional consistency, with some participants increasing lateral displacement, whilst others decreased its magnitude. Distance participant 7 increased the maximum lateral displacement of the finger, wrist and elbow by 0.16 m, 0.06 m and 0.05 m respectively when distance swimming relative to sprinting (Figure 4.16). Distance participant 8 decreased the maximum lateral displacement of the finger, wrist and elbow by 0.11 m, 0.09 m and 0.05 m when distance swimming relative to sprinting (Figure 4.17).

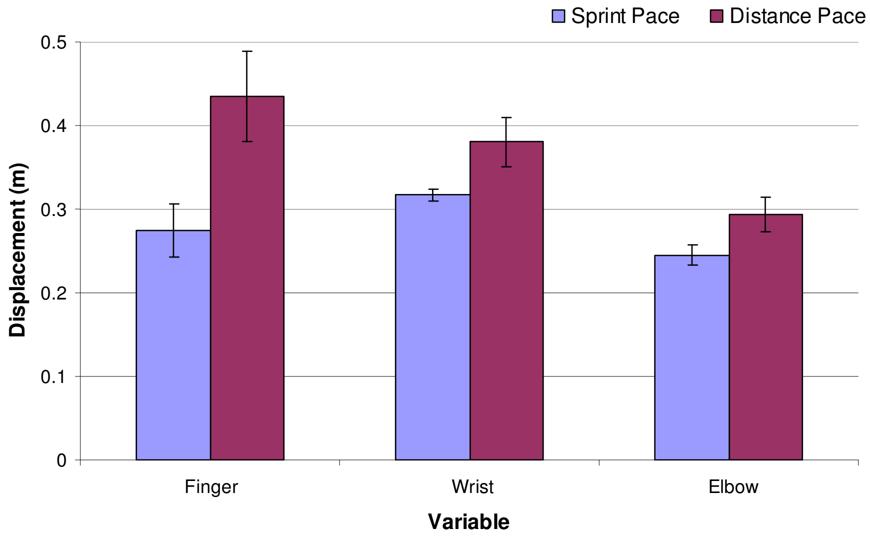


Figure 4.16: Distance participant 7- maximum lateral displacement of the finger, wrist and elbow. Error bars are the SD over three trials.

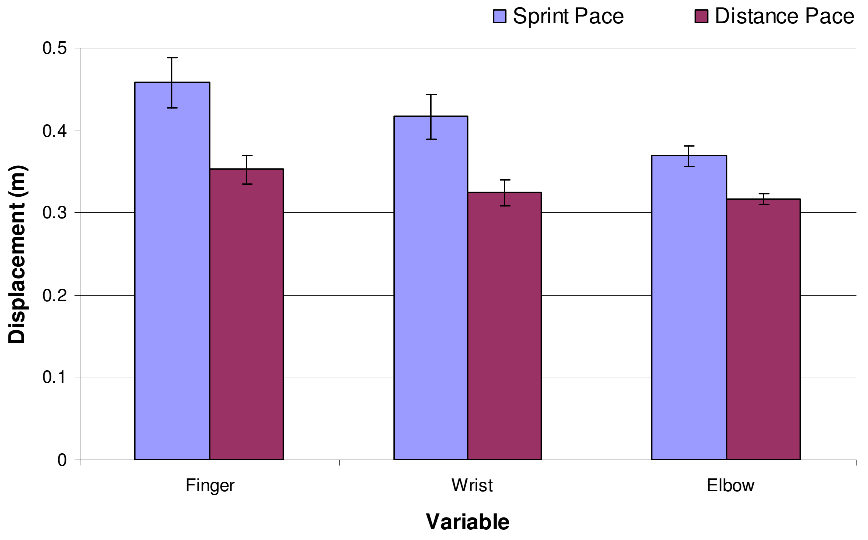


Figure 4.17: Distance participant 8- maximum lateral displacement of the finger, wrist and elbow. Error bars are the SD over three trials.

4.3.1.5. Time to Finger Maximum Lateral Displacement

The time to maximum lateral displacement of the finger was significantly different between paces (p= 0.041). Figure 4.18 indicates that SG and DG take 19.76% SC and 2.50% SC longer respectively to reach maximum lateral displacement of the finger, when distance swimming relative to sprinting. A large effect size was found between paces within the SG (d= 1.80) and a small effect within the DG (d= 0.17). Moreover, post hoc analysis revealed that within the SG, the difference approached significance (p= 0.0175) between paces, but not within the DG (p= 0.7473).

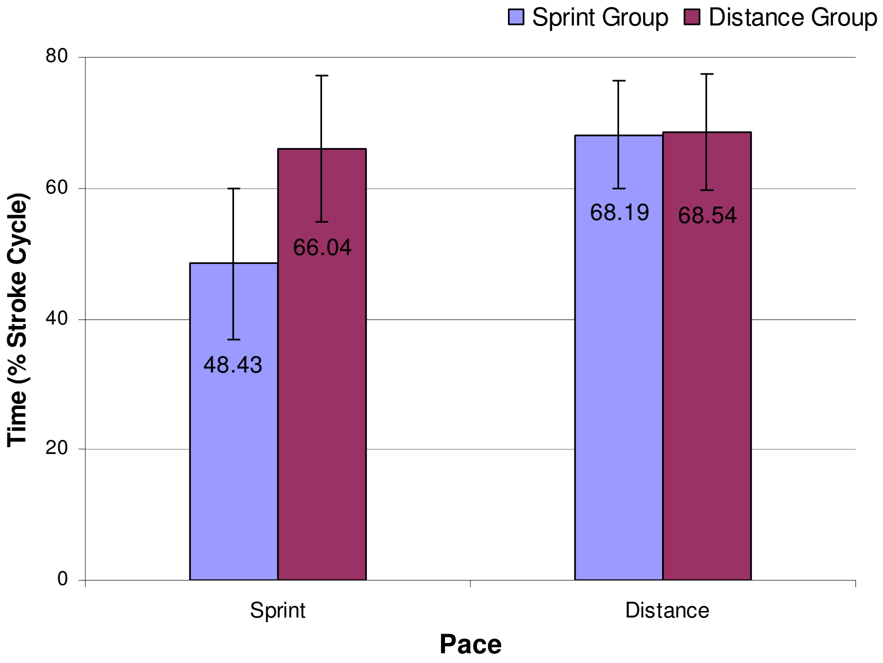


Figure 4.18: Time to maximum lateral displacement of the finger- SG vs. DG at sprint and distance pace. Mean time (%SC) values are indicated. Error bars represent 95% confidence interval of the true mean.

4.3.1.6. Lateral Displacement Range

The difference in lateral displacement range of the finger between paces approached significance (p= 0.067), with a moderate effect size found for the SG (d= 0.76) and a small effect size for the DG (d= 0.33) (Table 4.4). There was no significant difference between groups (p= 0.359) nor a significant pace-group interaction (p= 0.738), despite a moderate effect size within the sprint pace trials (d= 0.53) and a small effect size within the distance pace trials (d= 0.35) between the groups. No significant difference was found between paces for the wrist (p= 0.166) and elbow range (p= 0.784), despite a moderate effect size found for each of these variables (Table 4.4).

	Effect Size SG	*Effect Size DG*	*Effect Size Sprint*	*Effect Size Distance*
Finger	-0.76	-0.33	-0.53	-0.35
Wrist	-0.45	-0.27	-0.71	-0.44
Elbow	-0.24	0.19	-0.09	0.46

Table 4.4: Effect size lateral displacement range of the finger, wrist and elbow for SG and DG. The effect size between paces within the SG and DG are presented on the left side columns. The effect size between groups within the sprint and distance paces are presented on the right side columns.

Figures 4.19 and 4.20 indicate that six participants changed the magnitude of finger lateral displacement range between paces. Sprint participants 3, 6, 7, and distance participants 1 and 4 all increased the finger lateral displacement range at distance than sprint pace. Distance participant 8 had a greater finger lateral displacement range when sprinting than distance swimming. These results indicate that despite a lack of significant difference in group means between paces, some individuals changed this variable between paces. However, there was a lack of consistency among individuals in terms of the direction of change. Consequently, further investigation that includes a larger sample and a greater number of trials is warranted to examine individual and group effects more closely.

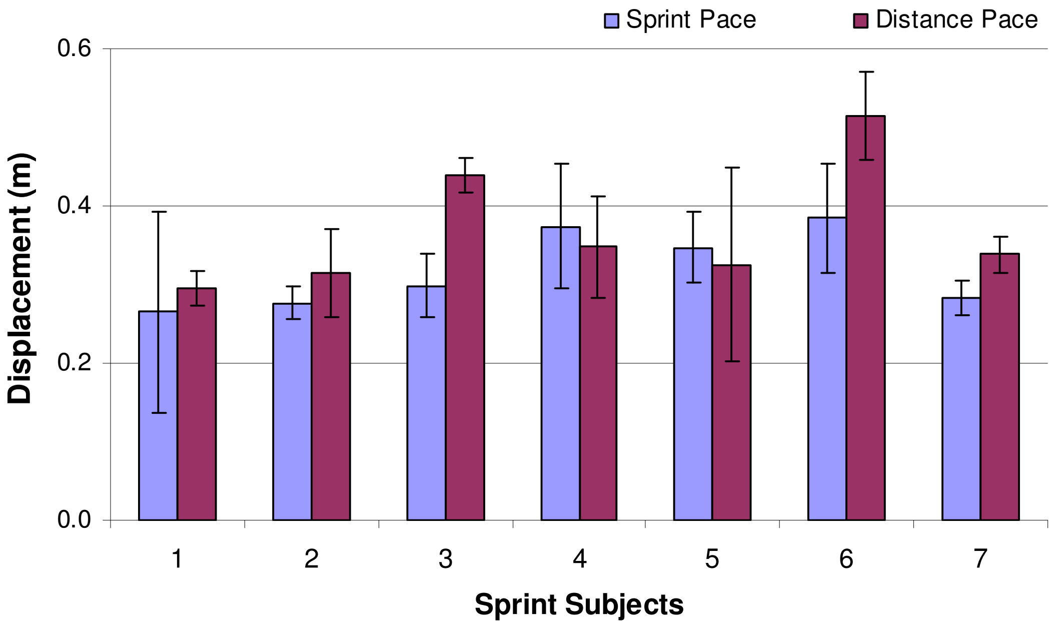


Figure 4.19: SG: lateral range of displacement of the finger- sprint vs. distance pace.

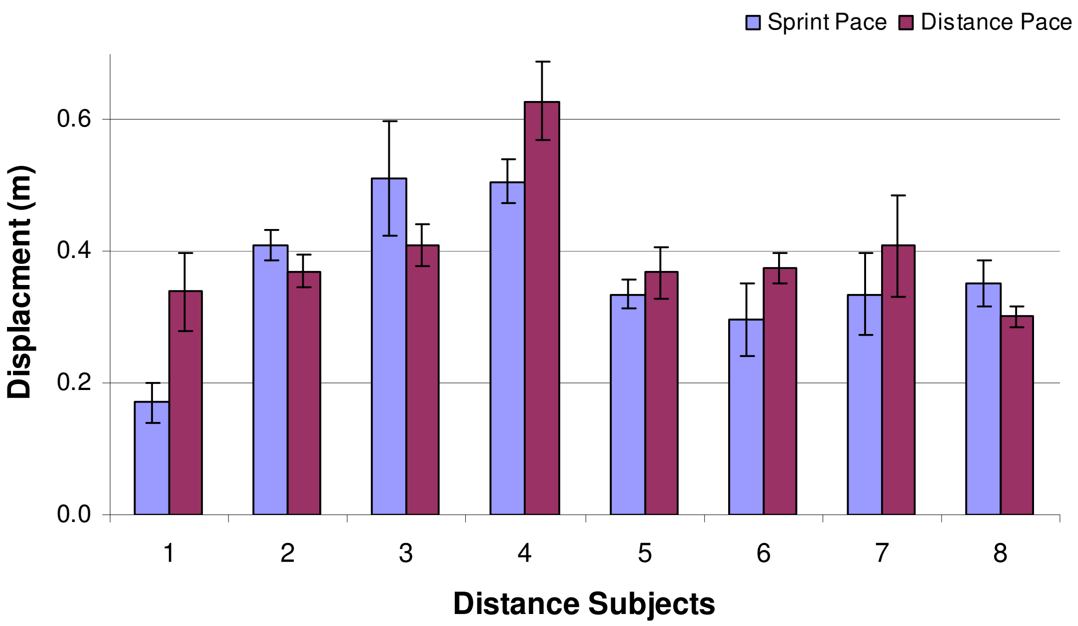


Figure 4.20: DG: lateral range of displacement of the finger- sprint vs. distance pace.

Figures 4.21 and 4.22 indicate that the DG had a greater mean lateral displacement range of the finger and wrist than SG at both paces. However, due to the large error of individual swimmers these differences did not reach statistical significance.

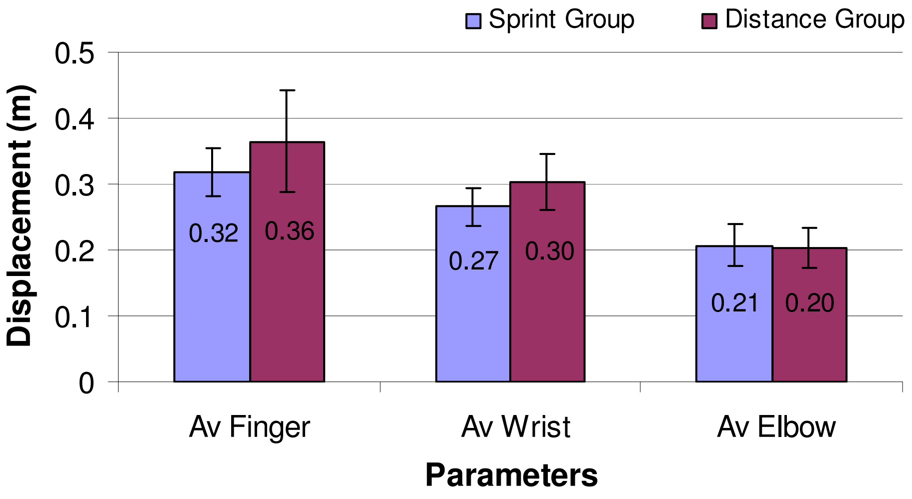


Figure 4.21: Lateral displacement range of the finger, wrist and elbow during the sprint pace- SG vs. DG. Mean displacement (m) values are indicated. Error bars represent 95% confidence interval of the true mean.

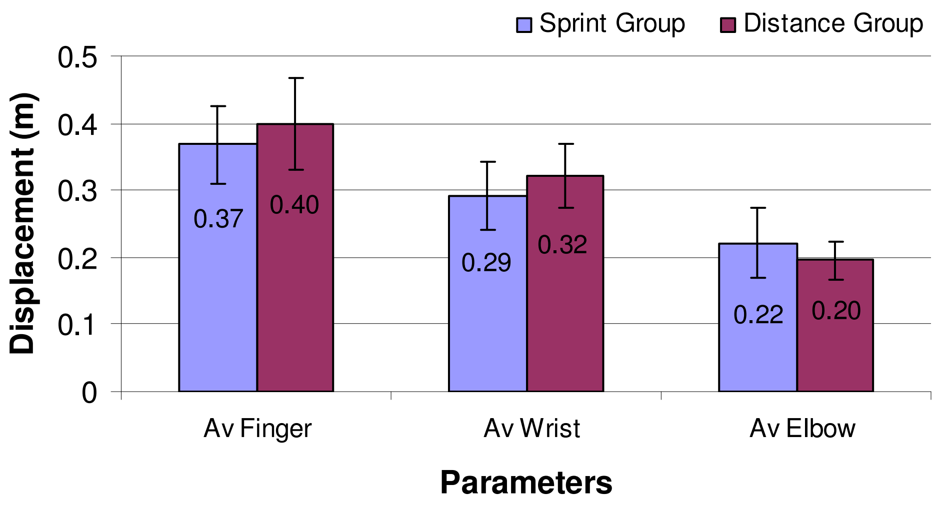


Figure 4.22: Lateral displacement range of the finger, wrist and elbow during the distance pace-SG vs. DG. Mean displacement (m) values are indicated. Error bars represent 95% confidence interval of the true mean.

Figures 4.23-4.26 show the lateral displacement range of the finger, wrist and elbow of four participants who changed between sprint and distance swimming based on the magnitude of the error bars. Distance participants 1 (Figure 4.23) and 4 (Figure 4.24) increased the lateral displacement range of the finger and wrist when distance swimming, but not the elbow. Distance participant 8 (Figure 4.25) increased the lateral displacement range of the wrist and elbow, but not the finger, when sprinting. Sprint participant 3 (Figure 4.26) increased the lateral displacement range of the finger, wrist and elbow when distance swimming.

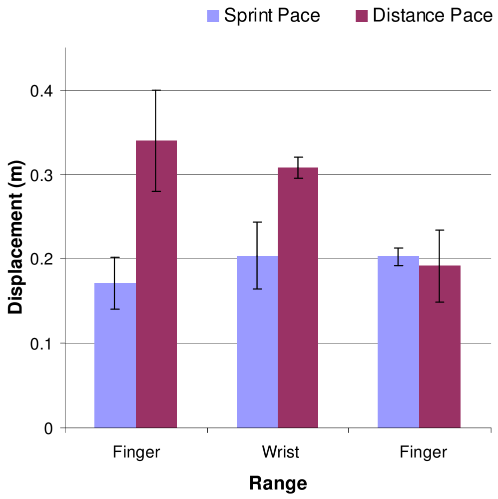


Figure 4.23: Distance participant 1: lateral range displacement- sprint vs. distance pace. Error bars are the SD over three trials.

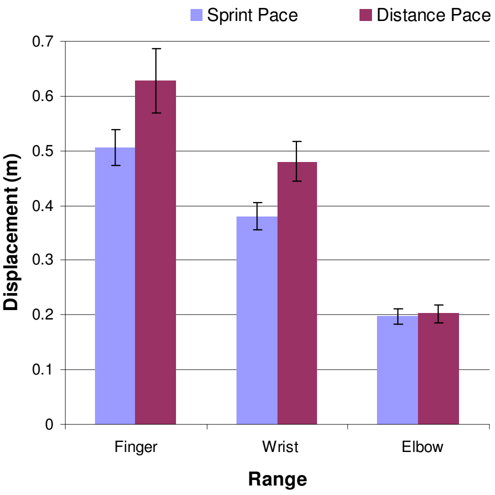


Figure 4.24: Distance participant 4: lateral range displacement- sprint vs. distance pace. Error bars are the SD over three trials.

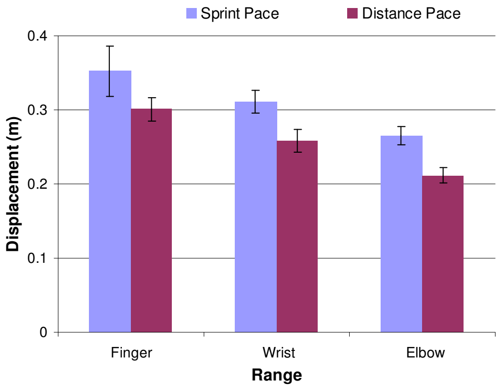


Figure 4.25: Distance participant 8: lateral range displacement- sprint vs. distance pace. Error bars are the SD over three trials.

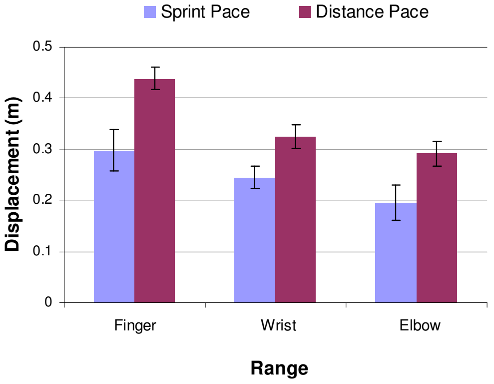


Figure 4.26: Sprint participant 3: lateral range displacement- sprint vs. distance pace. Error bars are the SD over three trials.

4.3.2. Elbow Angle

Table 4.5 presents the effect sizes for the elbow angle variables.

	Effect Size SG	*Effect Size DG*	*Effect Size Sprint*	*Effect Size Distance*
Max Left	0.57	0.02	0.49	-0.15
Max Right	1.21	0.37	0.57	-0.30
Time to Max Left	-0.28	-1.92	-0.02	-0.81
Time to Max Right	0.29	-0.37	0.24	-0.45
Min Left	0.22	-0.11	-0.54	-0.70
Min Right	-0.03	0.14	-0.18	-0.01
Time to Min Left	0.72	-0.13	0.17	-0.44
Time to Min Right	-1.04	-0.21	-0.84	0.51

Table 4.5: Effect size elbow angle data for SG and DG. The effect size between paces within the SG and DG are presented on the left side columns. The effect size between groups within the sprint and distance paces are presented on the right side columns.

4.3.2.1. Maximum Elbow Angle

The maximum right elbow angle approached significance between paces (p= 0.056) (Figure 4.27). Post hoc analysis revealed a significant difference between the paces within the SG (p< 0.0125) but not within the DG (p= 0.442), which was supported by the effect size data (Table 4.5). There was no significant difference between groups (p= 0.372) nor a significant pace-group interaction (p= 0.985), despite a moderate effect size between groups when sprinting (d= 0.57) and a small effect when distance swimming (d= 0.30). There was no significant difference with respect to the maximum left elbow angle between paces (p= 0.151), groups (p= 0.342), nor a significant pace-group interaction (p= 0.743). However, a moderate effect size was found across paces and groups within the SG and sprint pace trials respectively in relation to the maximum left elbow angle variable.

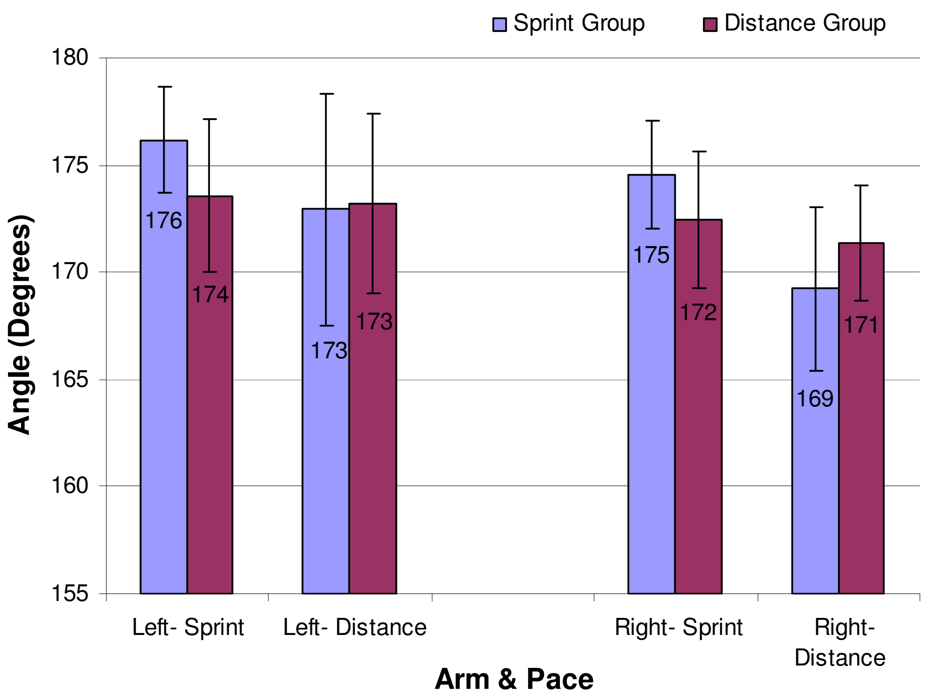


Figure 4.27: Maximum elbow angle during the underwater phase- SG vs. DG at sprint and distance pace. Mean angle (degs) values are indicated. Error bars represent 95% confidence interval of the true mean.

4.3.2.2. Time to Max Elbow Angle

The time to maximum right elbow angle was not significantly different between paces (p= 0.931), nor groups (p= 0.894), and the pace-group interaction (p= 0.320) was not significant (Figure 4.28). The time to maximum left elbow angle was not significantly different between paces (p= 0.178), groups (p= 0.406) and the pace-group interaction (p= 0.181) was not significant. However, the DG presented a large effect size across paces in relation to the time to maximum left elbow angle, which was supported by a significant difference between paces within the DG (p= 0.0020) following post hoc analysis. Figure 4.29 indicates that the DG generally take longer to reach maximum left elbow angle at distance pace than sprinting. The effect size data (Table 4.5) also present a large effect size between groups, but only within the distance pace trials.

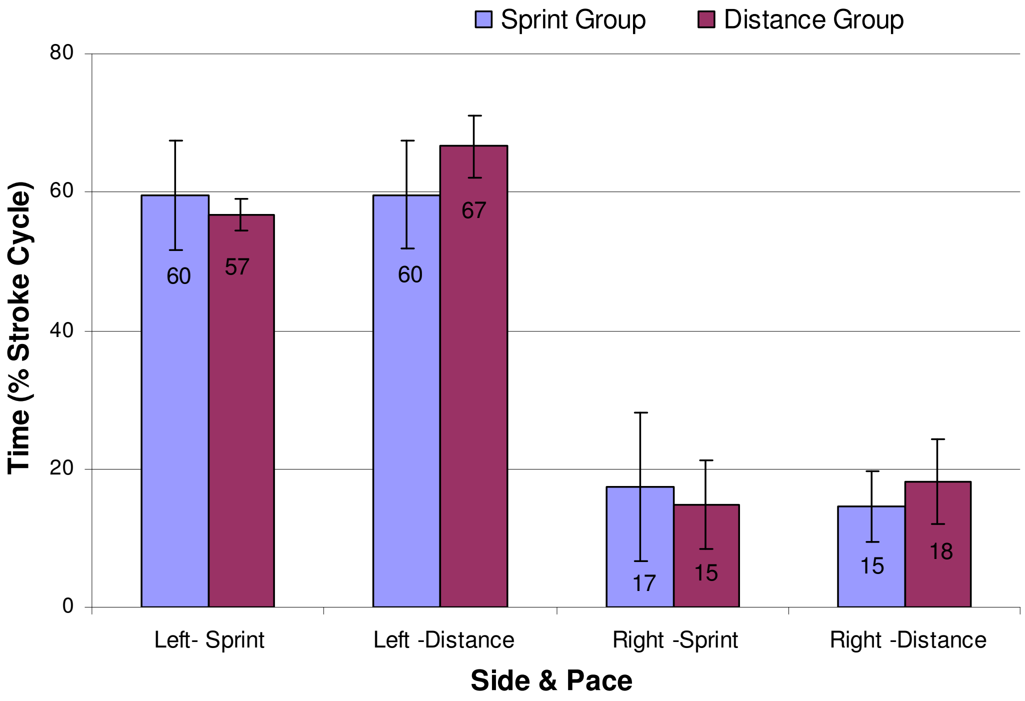


Figure 4.28: Time to maximum elbow angle of both arms- SG vs. DG at sprint and distance pace. Mean time (%SC) values are indicated. Error bars represent 95% confidence interval of the true mean.

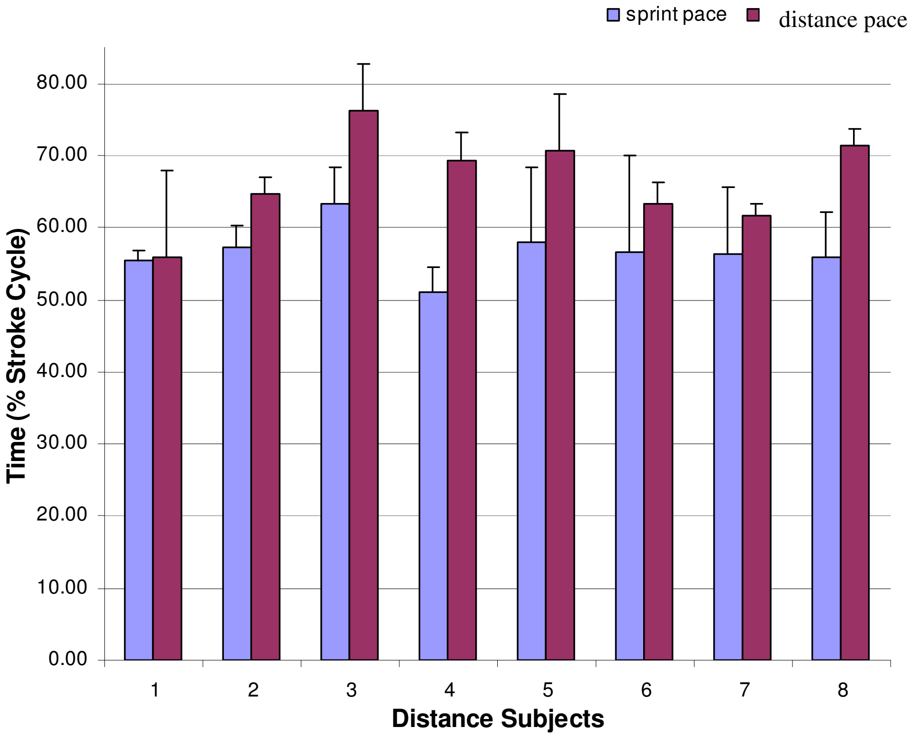


Figure 4.29: DG: Time to maximum left elbow angle- sprint vs. distance pace.

4.3.2.3. Minimum Elbow Angle

There was no significant difference between paces for either the right (p= 0.848) or left (p= 0.658) minimum elbow angle (Figure 4.30), which is further supported by a low effect size for either group across paces (Table 4.5). The groups were not significantly different for the right (p= 0.831) or left (p= 0.211) minimum elbow angle, despite a moderate effect size found between groups at both paces in relation to the minimum left elbow angle (Table 4.5). There was no pace-group interaction for the right (p= 0.751) and left minimum elbow angle (p= 0.424).

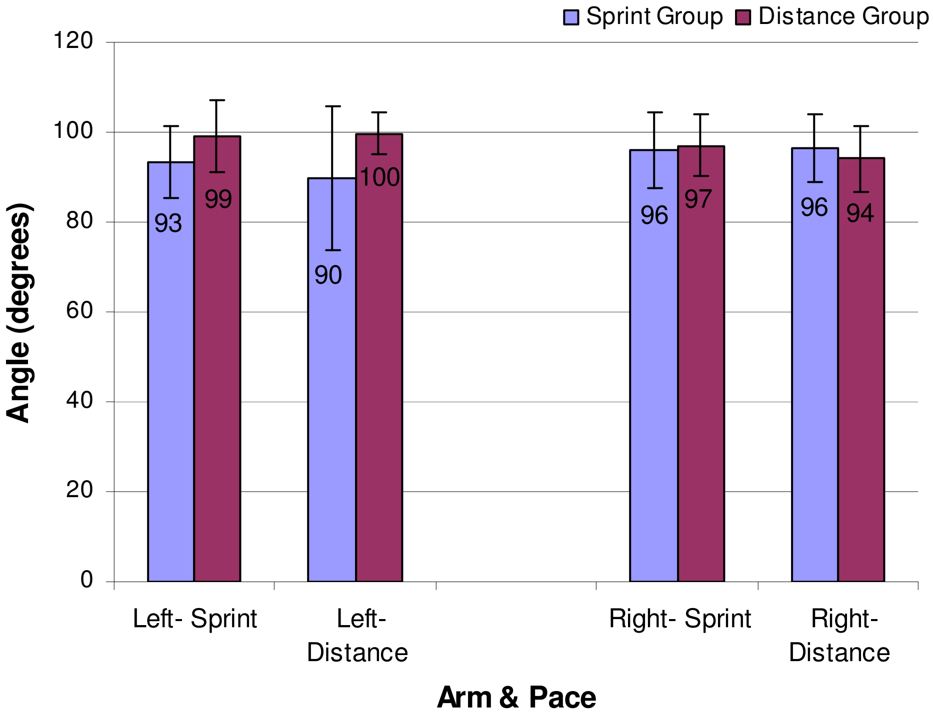


Figure 4.30: Minimum elbow angle of both arms- SG vs. DG at sprint and distance pace. Mean angle (degs) values are indicated. Error bars represent 95% confidence interval of the true mean.

Figure 4.31 shows the minimum elbow angles of five individuals who changed between paces. Three participants (SG- 6 and 3; DG- 3) decreased the minimum elbow angle at distance pace than sprinting, whereas the other two participants (DG- 1 and 7) increased this angle at distance pace (Figure 4.31). These results indicate that some individuals changed this variable between paces, even though there was no significant difference between paces amongst the group means. However, there was a lack of consistency among individuals in terms of the direction of change.

Consequently, further investigation that includes a larger sample and a greater number of trials is warranted to examine individual and group effects more closely.

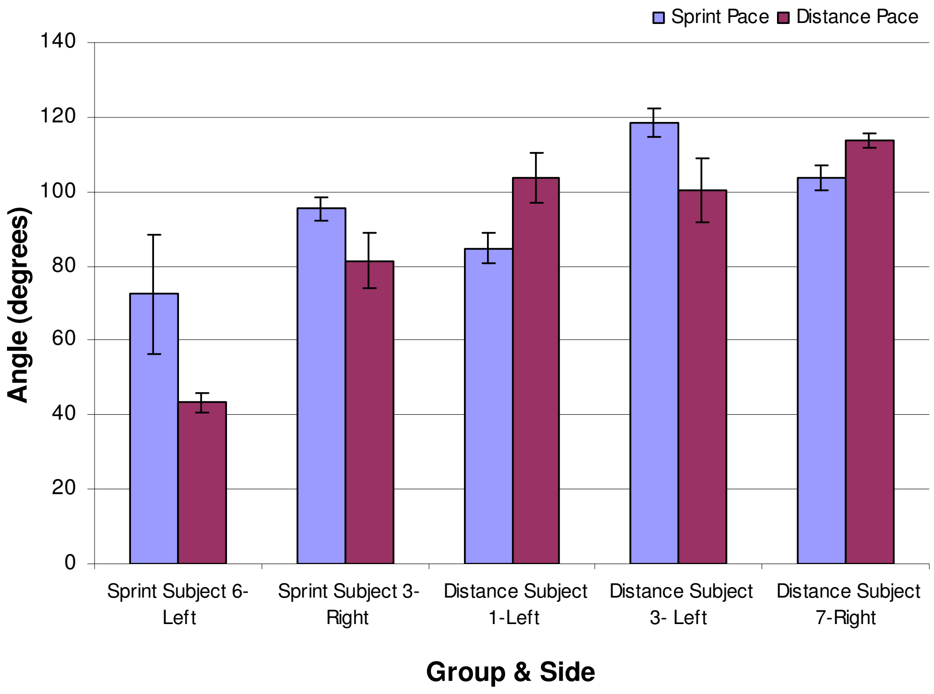


Figure 4.31: Illustration of the participants who changed the minimum elbow angle with a change in swim pace. Sprint participants 6, 3 and distance participant 3 decrease the minimum elbow angle when swimming at a distance pace. Distance participants 1 and 7 increase the elbow angle when swimming at a distance pace.

4.3.2.4. Time to Minimum Elbow Angle

There was no significant difference between paces with respect to the time to left minimum elbow angle (p= 0.366) (Figure 4.32), despite a moderate effect size found within the SG (d= 0.72) across paces in relation to this variable. There was no significant difference between groups (p= 0.594) nor a significant pace-group interaction (p= 0.200). The time to the minimum right elbow angle approached significance (p= 0.067) between paces with both groups taking longer to reach the minimum right elbow angle during distance than sprint pace. The effect size data (Table 4.5) present a large and small effect size within the SG and DG respectively across paces in relation to the time to minimum right elbow angle. There was no significant difference between groups (p= 0.897) nor a significant pace-group interaction (p= 0.174) in relation to the time to minimum right elbow angle, despite a large effect size found between groups within the sprint trials (d= 0.84) and a moderate effect size within the distance trials (d= 0.51).

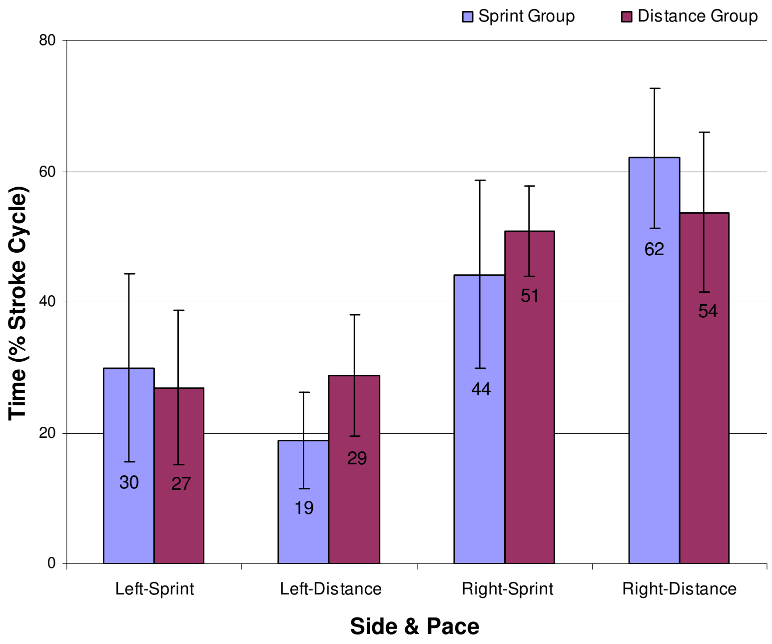


Figure 4.32: Time (%SC) to minimum elbow angle of both arms- SG vs. DG at both paces. Mean time (%SC) values are indicated. Error bars represent 95% confidence interval of the true mean.

4.3.2.5. Elbow Angle Variables

The seven elbow angle variables examined in this study are presented in Figure 4.33, numerical data in Table 4.6 and effect size data in Table 4.7.

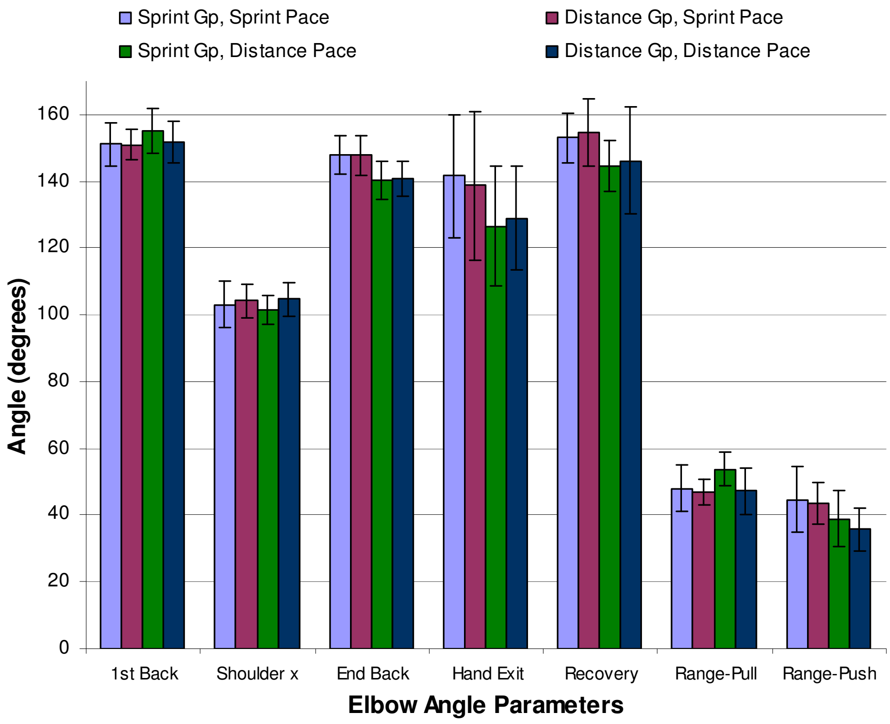


Figure 4.33: Elbow angle at various events during the SC- SG vs. DG at sprint and distance pace. Error bars represent 95% confidence interval of the true mean.

	Sprint Pace	*Distance Pace*	*Difference*
1st Back- SG	151.14 ± 8.65	155.15 ± 6.24	↑ 4.01
1st Back- DG	150.99 ± 9.75	151.73 ± 8.80	↑ 0.74
Shoulder X- SG	103.18 ± 9.28	101.37 ± 6.78	↓ 1.81
Shoulder X- DG	104.18 ± 6.25	104.69 ± 7.23	↑ 0.51
End Back- SG	147.83 ± 7.87	140.31 ± 8.15	↓ 7.52
End Back- DG	147.88 ± 8.53	140.79 ± 7.52	↓ 7.09
Hand Exit- SG	141.51 ± 24.64	126.56 ± 30.11	↓ 14.95
Hand Exit- DG	138.75 ± 26.05	128.98 ± 22.69	↓ 9.77
Recovery- SG	153.04 ± 10.01	144.50 ± 13.50	↓ 8.54
Recovery- DG	154.73 ± 11.18	146.28 ± 23.12	↓ 8.45
Range of Pull- SG	47.96 ± 9.40	53.77 ± 5.30	↑ 5.81
Range of Pull- DG	46.81 ± 7.42	47.28 ± 10.20	↑ 0.47
Range of Push- SG	44.65 ± 13.24	38.94 ± 8.55	↓ 5.71
Range of Push- DG	43.70 ± 11.88	35.72 ± 9.22	↓ 7.98

Table 4.6: Elbow angle variables (degrees) for SG and DG. Differences between the sprint and distance trials.

	Effect Size SG	*Effect Size DG*	*Effect Size Sprint*	*Effect Size Distance*
1st Back	-0.53	-0.08	0.02	0.44
Shoulder	0.22	-0.08	-0.13	-0.47
End Back	0.94	0.88	-0.01	-0.06
Hand Exit	0.54	0.40	0.11	-0.09
Recovery	0.72	0.47	-0.16	-0.09
Range of Pull	-0.76	-0.05	0.14	0.78
Range of Push	0.51	0.75	0.08	0.36

Table 4.7: Effect size data for elbow angle variables. The effect size between paces within the SG and DG are presented on the left side columns. The effect size between groups within the sprint and distance paces are presented on the right side columns.

The 1st back elbow angle was not significantly different between paces (p= 0.186), however the SG did show a moderate effect size between paces. There was no significant difference across groups (p= 0.669), and no significant pace-group interaction (p= 0.355). The shoulder x elbow angle was not significantly different between paces (p= 0.712). The groups (p= 0.540) and pace-group interaction (p= 0.511) were not significantly different. The end back elbow angle was significantly different between paces (p = 0.007), with both groups showing a large effect size for this variable (Table 4.7). These results indicate that both the SG and DG reduced the end back elbow angle by 7.52° and 7.09° respectively when distance swimming relative to sprinting. No significant difference was found between groups (p= 0.940) and no pace-group interaction (p= 0.928). The hand exit elbow angle was not significantly different between paces (p= 0.099), however the SG showed a moderate effect size (d= 0.54), whilst the DG showed a small effect size (d= 0.40) across paces. No significant difference was found between groups (p= 0.989) and there was no significant pace-group interaction (p= 0.716) for the elbow angle at hand exit. Nevertheless, Figures 4.34 and 4.35 indicate that seven participants did change the magnitude of elbow angle at hand exit between paces based on the magnitude of the error bars. Sprint participants 3, 4, and 8, and distance participants 4, 7, and 8 all reduced the elbow angle magnitude at distance than sprint pace. Distance participant 3 increased the elbow angle magnitude at distance than sprint pace. Despite the majority of participants reducing elbow angle at hand exit, this was not a consistent trend across swimmers and requires further investigation.

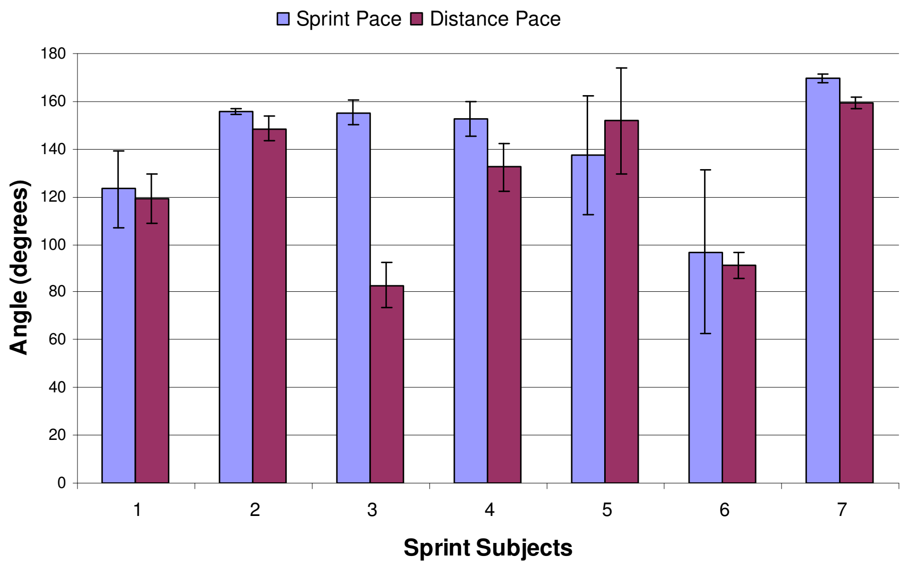


Figure 4.34: SG: Elbow angle (degrees) at hand exit between sprint and distance pace. Participants 3, 4, and 8 all changed the magnitude between paces.

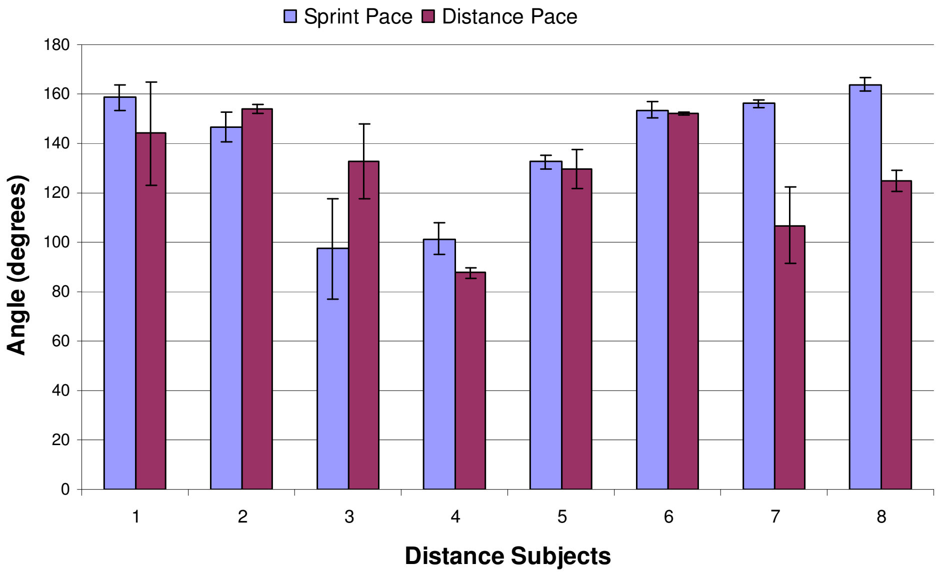


Figure 4.35: DG: Elbow angle (degrees) at hand exit between sprint and distance pace. Participants 3, 4, 7, and 8 all changed the magnitude between paces.

The difference in elbow angle at recovery (as the hand re-enters the water) between paces approached significance (p= 0.084), with both groups showing a moderate effect size between paces (Table 4.7). Figure 4.33 and Table 4.6 indicate that both groups had a greater elbow recovery angle when sprinting than distance swimming. There was no significant difference between groups (p= 0.798) nor a significant pace-group interaction (p= 0.993). Figures 4.36 and 4.37 indicate that sprint participant 2 and distance participants 7 and 8 clearly reduced the elbow angle at recovery when swimming at distance than sprint pace.

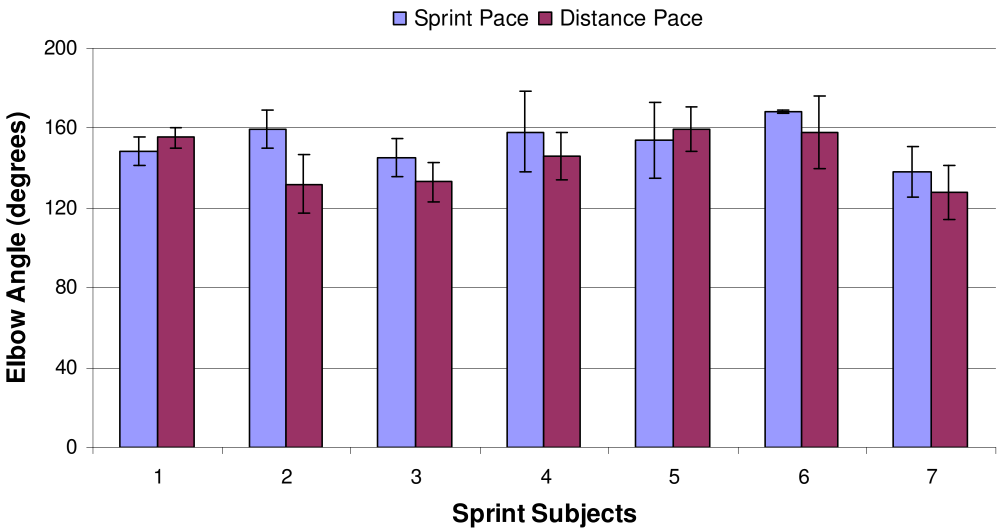


Figure 4.36: SG: Elbow angle (degrees) at recovery between sprint and distance pace.

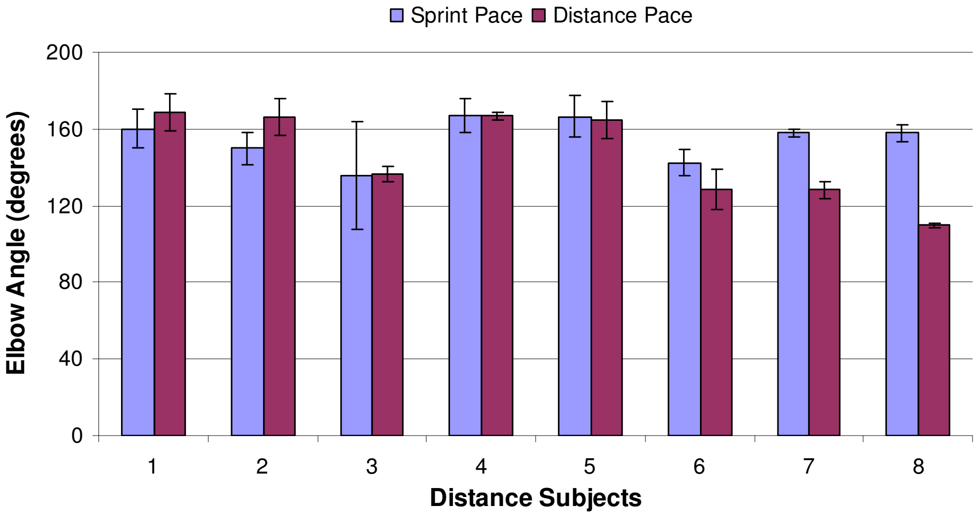


Figure 4.37: DG: Elbow angle (degrees) at recovery between sprint and distance pace.

The elbow angle range during the pull phase was not significantly different between paces (p= 0.270) or groups (p= 0.275) and there was no significant pace-group interaction (p= 0.346). However, a moderate effect size was found within the SG between paces (d= 0.76) and between the groups within the distance pace trials (d= 0.78). The elbow angle range during the push phase was significantly different between paces (p = 0.05), with both SG and DG showing a moderate effect size (Table 4.7), and reducing the range by 5.71° and 7.98° respectively at distance relative to sprint pace. There was no significant difference between groups (p= 0.659) and there was no significant pace-group interaction (p= 0.659).

4.3.3. Time Spent in Each of the Stroke Phases

The duration of each stroke phase was analysed with respect to the first and second arm entering the water. This was performed as the same arm did not always enter the water across trials and swimmers. The duration of all the stroke phases (entry, pull, push, and recovery) and the instant at which the hand exited the water was significantly different between paces for both groups (p< 0.05). The effect sizes presented in Table 4.8, show that the SG had a large effect size between paces in relation to all the stroke phases, whilst the DG showed large effect size during the entry phase and a small effect size during the pull phase and moment of hand exit.

Phases	*Effect Size SG*	*Effect Size DG*	*Effect Size Sprint*	*Effect Size Distance*
Entry	-1.89	-1.59	0.73	0.40
Pull	1.34	0.22	-0.07	-0.12
Push	1.15	0.18	-1.16	-0.54
Recovery	1.10	0.17	-0.39	-0.25
Hand Exit	-1.33	-0.19	0.15	0.28

Table 4.8: Effect size data for the stroke phases. The effect size between paces within the SG and DG are presented on the left side columns. The effect size between groups within the sprint and distance paces are presented on the right side columns.

There was no significant difference between groups for the entry (p= 0.244), hand exit (p= 0.610) or recovery (p= 0.489) phase duration. The pace-group interaction was not significant for the entry (p= 0.649), pull (p= 0.975), push (p= 0.366), hand exit (p= 0.794), or recovery (p= 0.890) phases. The difference between groups in duration of the pull phase was not significant with respect to the first arm (p= 0.853) (Figure 4.38), but was significantly different between groups with respect to the second arm (p= 0.045) (Figure 4.39).

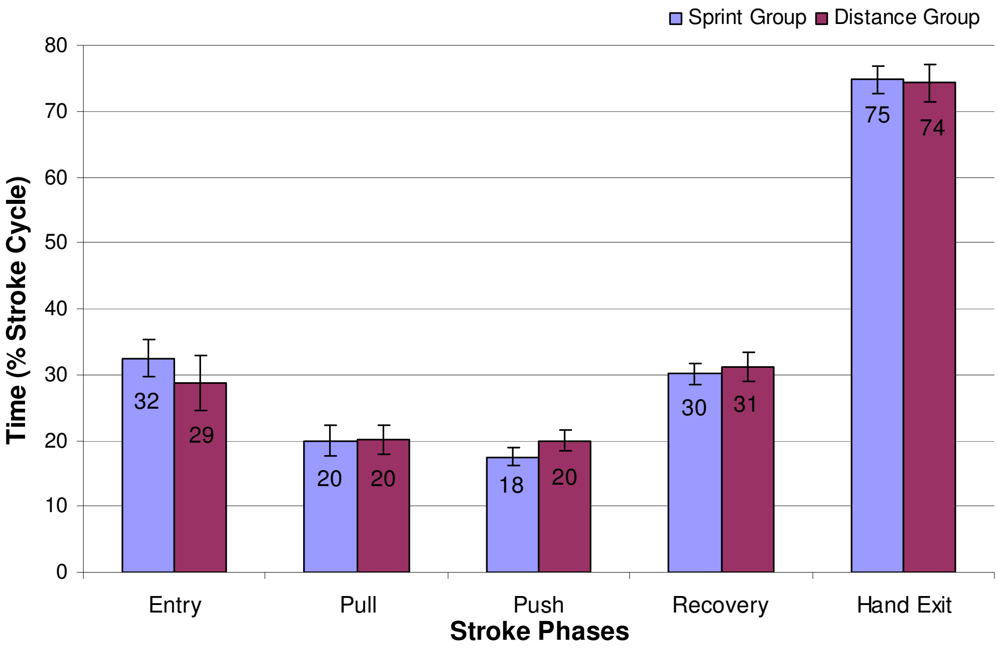


Figure 4.38: Stroke phase durations (% SC) with respect to the first arm entry, at sprint pace- SG vs. DG. Mean stroke phase duration data are indicated. Error bars represent 95% confidence interval of the true mean.

Post hoc analysis revealed that this change occurred during the sprint trials (p= 0.0069). It was found that the DG spent longer in the pull phase than SG (16.13% SC vs. 8.76% SC) at sprint pace with respect to the second arm entry (Figure 4.39). In comparison, the duration of the pull phase with respect to the first arm entering was 19.95% and 20.17% SC for the SG and DG respectively at sprint pace.

The difference between groups in duration of the push phase approached significance (p= 0.082) with respect to the first arm entry. A large effect size was found between groups within the sprint trials (d= 1.16) during the push phase, whilst a moderate effect size was found within the distance trials (d= 0.54). Figure 4.38 indicates that the DG spent longer in the push phase than the SG, particularly when sprinting.

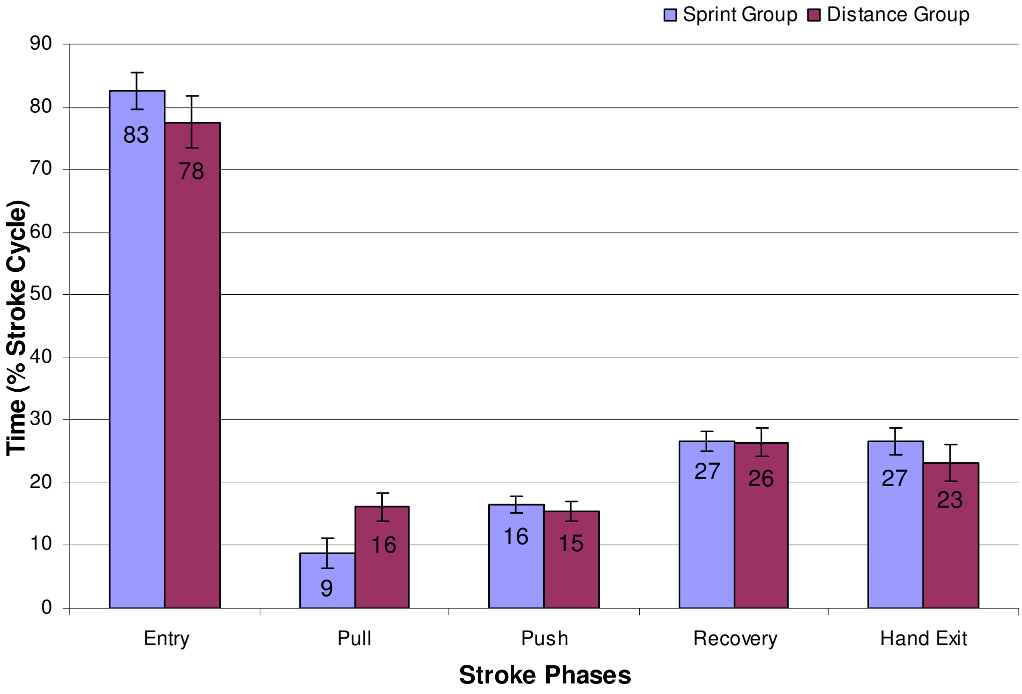


Figure 4.39: Durations (%SC) of stroke phases of the second arm - SG vs. DG at sprint pace. Here the entry phase is represented as the instant the second hand enters the water. Mean stroke phase duration data are indicated. Error bars represent 95% confidence interval of the true mean.

Figures 4.40 and 4.41 indicate the duration of the stroke phase changes between paces for the SG and DG respectively. Both groups spent significantly longer in the entry phase when distance swimming than when sprinting (SG- 9.05%; DG- 10.37%). All swimmers spent relatively less time in the pull, push and recovery phases at distance than sprint pace. Post hoc analysis for the pull phase revealed a significant difference between paces within the DG (p= 0.004), with the SG approaching significance (p= 0.0188). Post hoc analysis for the push phase revealed a significant difference between paces within the DG (p= 0.0056) but not within the SG (p= 0.032). The swimmers spent less time in the push phase at distance than sprint pace. Post hoc analysis for the recovery phase revealed a significant difference between paces within the DG (p = 0.0082) and, again, the difference within the SG (p= 0.050) approached statistical significance. Swimmers increased the duration of the recovery phase when sprinting compared to distance swimming.

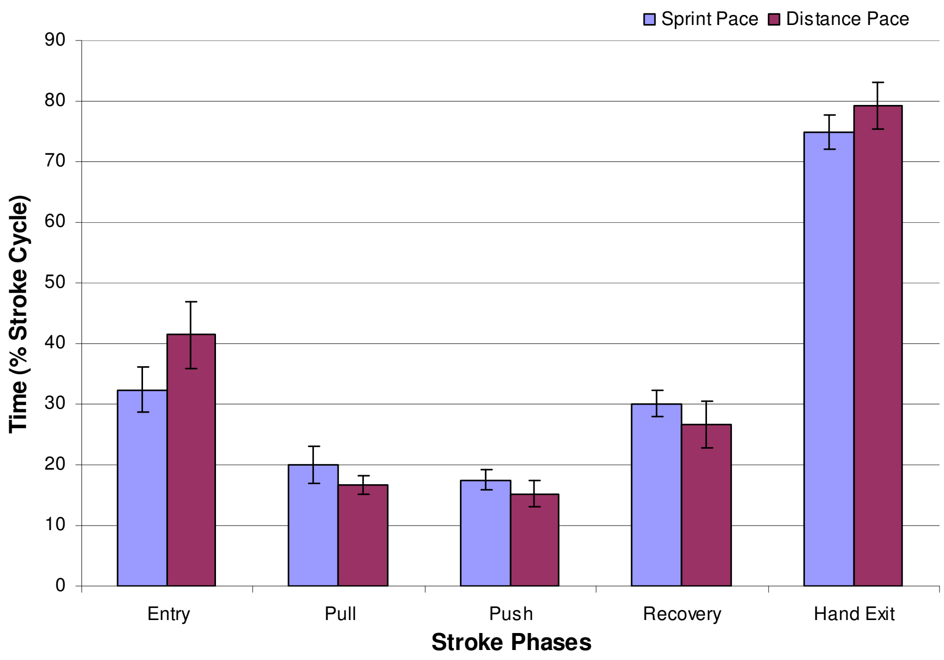


Figure 4.40: SG: stroke phase durations (%SC) - sprint vs. distance pace.

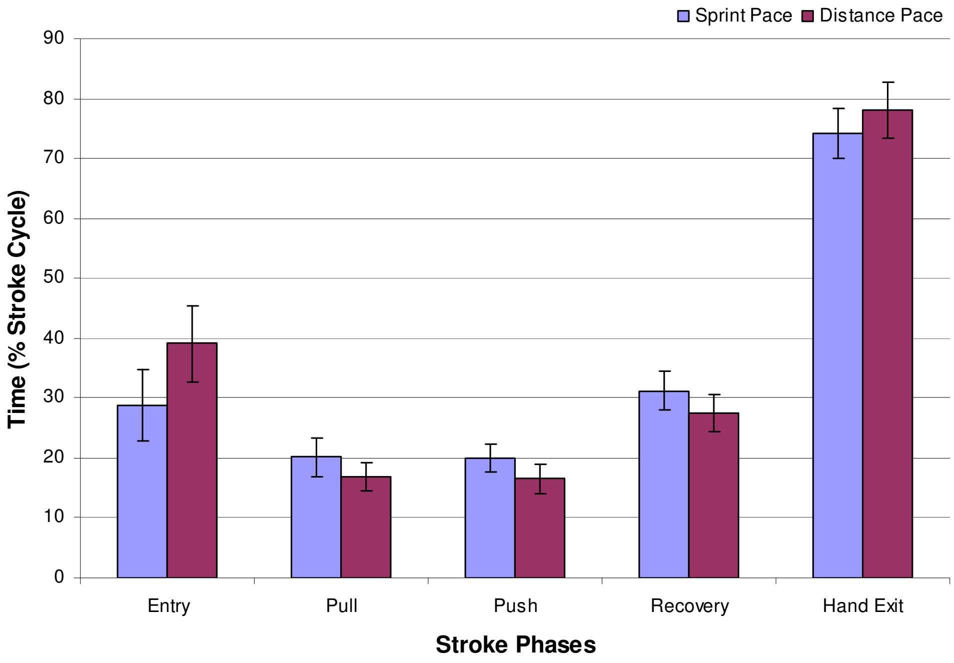


Figure 4.41: DG: stroke phase durations (%SC) - sprint vs. distance pace.

The later timing of the hand exiting was significantly different between paces with respect to the first arm entering (p= 0.04) and the second arm entering (p<0.001). At distance pace it took both groups longer to exit the hand. Post hoc analysis revealed a significant difference within the DG (p= 0.004) between paces, but not within the SG (p= 0.048) (Figure 4.42) with respect to the second arm exiting the water.

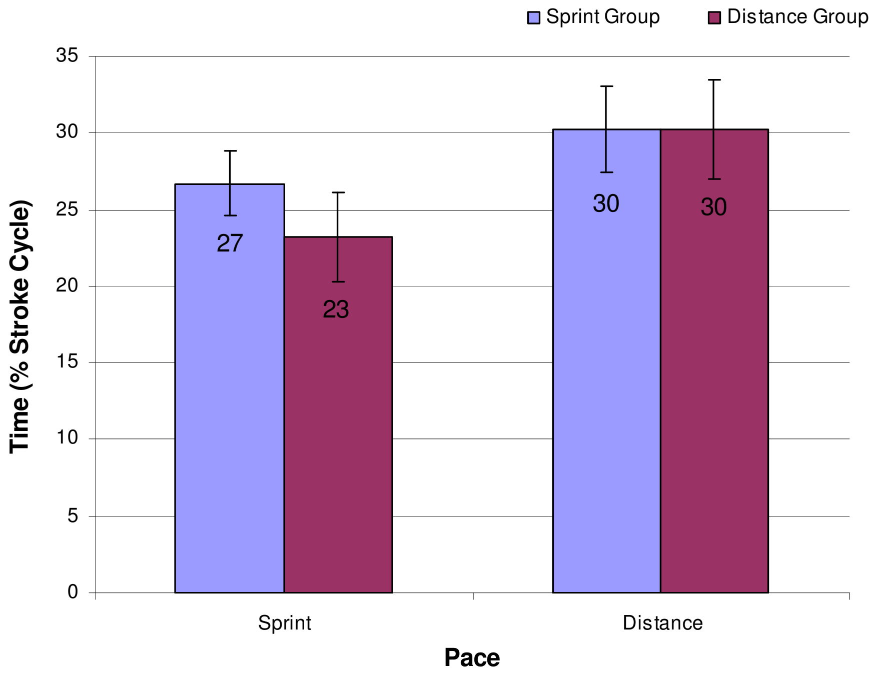


Figure 4.42: Occurrence (%SC) of hand exit phase for the second arm- SG vs. DG at sprint and distance pace. Mean time of hand exit values are indicated. Error bars represent 95% confidence interval of the true mean.

4.3.4. Shoulder and Hip Roll

Table 4.9 presents the effect size data for the shoulder and hip roll angle throughout the SC.

	Effect Size SG	*Effect Size DG*	*Effect Size Sprint*	*Effect Size Distance*
Max Shoulder, Left	-0.02	-0.29	0.78	0.37
Max Hip, Left	-0.85	-1.14	-0.34	0.15
Max Shoulder, Right	-0.79	-0.64	-1.01	-0.49
Max Hip, Right	-1.01	-0.95	-0.35	0.37
Time to Max Shoulder, Left	-0.30	-1.73	1.72	0.06
Time to Max Hip, Left	-1.87	-1.97	-0.30	-0.11
Time to Max Shoulder, Right	-0.61	-0.85	1.29	0.93
Time to Max Hip, Right	-1.39	-1.61	0.35	0.04
Total Shoulder Roll	-0.37	-0.49	0.06	-0.01
Total Hip Roll	-0.97	-1.26	-0.40	0.28

Table 4.9: Effect size data for the shoulder and hip roll variables. The effect size between paces within the SG and DG are presented on the left side columns. The effect size between groups within the sprint and distance paces are presented on the right side columns.

4.3.4.1. Maximum Shoulder and Hip Roll

Maximum left shoulder roll was not significantly different between paces (p= 0.602) or groups (p= 0.278), despite a moderate effect size (d= 0.78) between groups within the sprint pace trials. There was no significant pace-group interaction (p= 0.770). Figure 4.43 indicates that five participants changed the magnitude of left shoulder roll between paces. Sprint participant 1 and distance participant 5 produced a greater left shoulder roll when sprinting than distance swimming. Sprint participant 3, and distance participants 2 and 8 had a greater left shoulder roll magnitude when distance swimming than sprinting. These results indicated that despite a lack of significant difference in group means between paces, some individuals changed this variable between paces. However, there was a lack of consistency among individuals in terms of the direction of change. Consequently, further investigation that includes a longer sample and a greater number of trials is warranted to examine individual and group effects more closely.

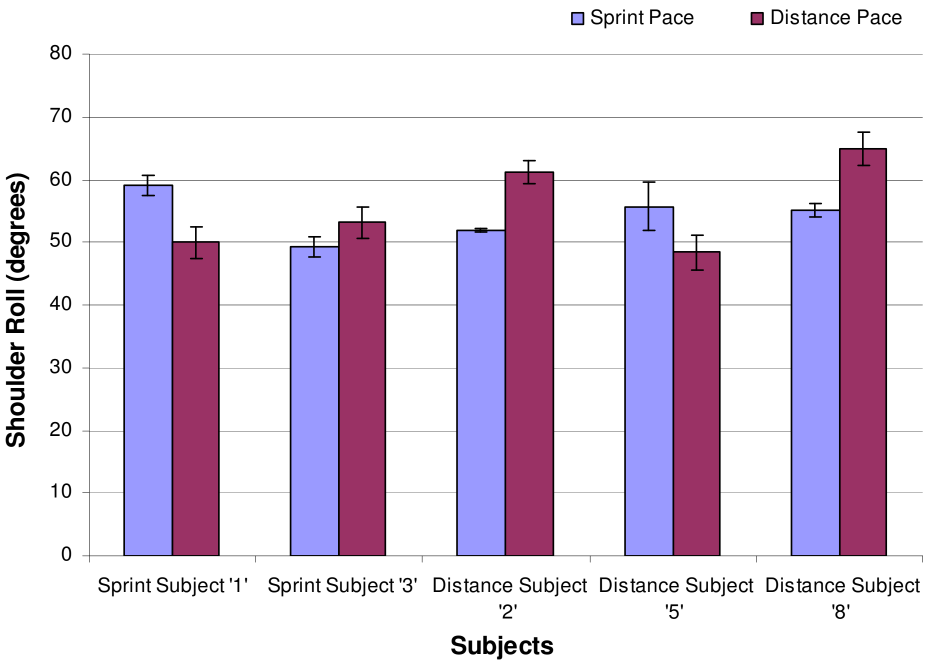


Figure 4.43: Illustration of the participants who adjust the maximum shoulder roll to the left dependent of the swim pace.

The difference between the two paces was significant (p= 0.044) with respect to the magnitude of maximum right shoulder roll, with a greater roll angle (3.78°- SG; 3.02°- DG) when distance swimming than sprinting. Moreover, both the SG and DG showed a moderate effect size across paces (d= 0.79 and d= 0.64, respectively). There was no significant difference between groups (p= 0.122) and no significant pace-group interaction (p= 0.122), despite a large effect size between groups within the sprint pace trials (d= 1.01).

Maximum left hip roll was significantly different between paces (p= 0.001), which was supported by the large effect size in both groups (Table 4.9). Both SG and DG significantly increased maximum left hip roll by 9.16° and 5.75° respectively when swimming at a distance than sprint pace. Post hoc analysis revealed a significant difference between paces within the DG (p= 0.006) while the difference between paces within the SG (p= 0.034) approached significance. No significant difference was found between groups (p= 0.974) and there was no significant pace-group interaction (p= 0.362). SG and DG increased the magnitude of maximum right hip roll by 10.76° and 5.33° respectively when distance swimming relative to sprinting. This change was significant between paces (p= 0.002), with both groups also showing a large effect size across paces (Table 4.9). There was no significant difference between groups (p= 0.731) and no significant pace-group interaction (p= 0.212).

4.3.4.1.1. Sprint Pace

Shoulder roll differed significantly between sides when sprinting (p< 0.001). Figure 4.44 indicates that both groups roll more to the left than to the right side by 11.60° (SG) and 3.99° (DG). Post hoc analysis revealed that the SG changed between sides (p= 0.004) more than the DG (Figure 4.44). There was no significant difference between groups (p= 0.891), but the side-group interaction was significant (p= 0.041), meaning that one group changed more than the other between the sides.

Hip roll differed significantly between sides (p= 0.03), with both groups rolling more to the right than the left side by 3.52° (SG) and 2.98° (DG) (Figure 4.44). There was no significant difference between groups (p= 0.473) and no significant side-group interaction (p= 0.887).

4.3.4.1.2. Distance Pace

Shoulder roll differed significantly between sides (p= 0.002) at distance pace. Figure 4.45 indicates that SG and DG roll the shoulders more to the left than to the right side by 7.95° and 2.36° respectively. There was no significant difference between groups (p= 0.988) but the side-group interaction approached significance (p= 0.063) with the SG group having a greater asymmetry than the DG group (Figure 4.45).

Hip roll differed significantly between sides (p= 0.05) but not between groups (p= 0.599), and there was no significant side-group interaction (p= 0.503) at distance pace. Figure 4.45 indicates that, at distance pace, both SG and DG rolled the hips more to the right than the left side by 5.12° and 2.62° respectively.

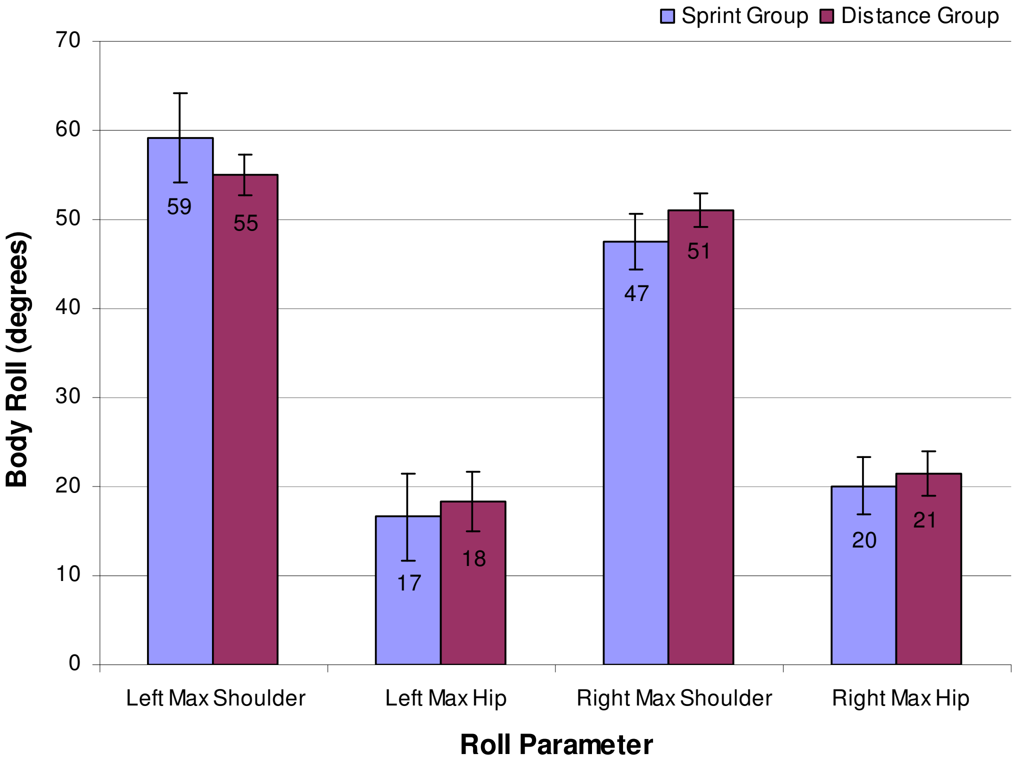


Figure 4.44: Maximum shoulder and hip roll at sprint pace- SG vs. DG. Mean shoulder and hip roll angle data are indicated. Error bars represent 95% confidence interval of the true mean.

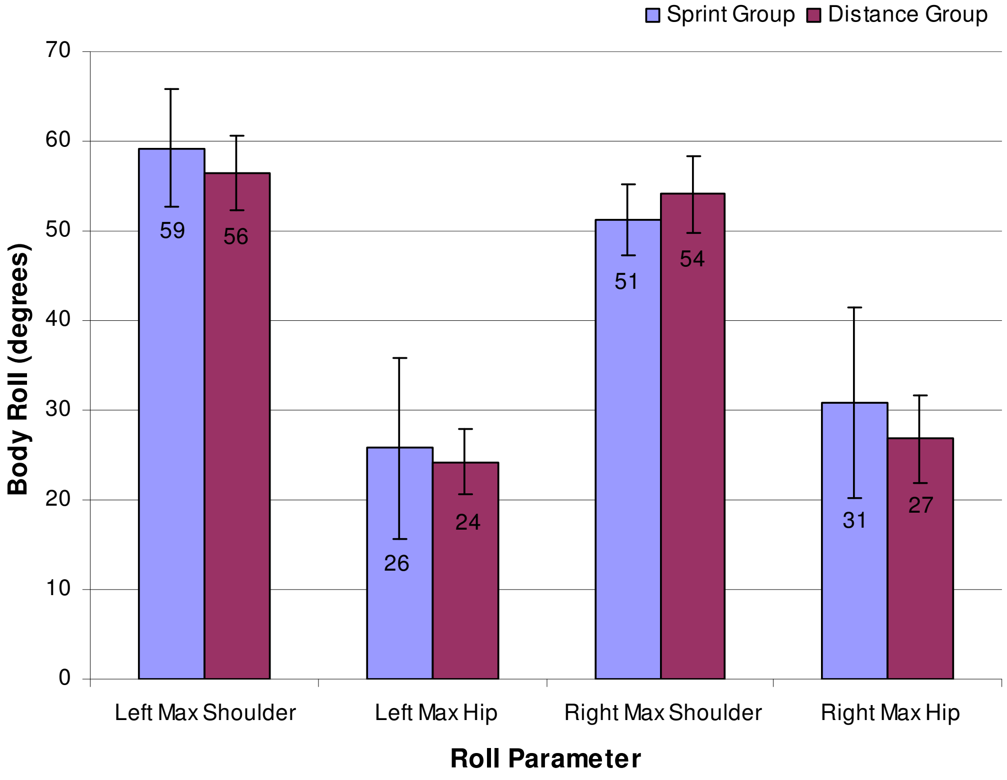


Figure 4.45: Maximum shoulder and hip roll at distance pace- SG vs. DG. Mean shoulder and hip roll angle data are indicated. Error bars represent 95% confidence interval of the true mean.

4.3.4.2. Time to Maximum Shoulder and Hip Roll

Time to maximum left shoulder roll was not significantly different between paces (p= 0.509) and the pace-group interaction (p= 0.836) was not significant. Post hoc analysis revealed a significant difference within the DG between paces (p= 0.0118) but not within the SG (p= 0.5510), which was supported by the large effect size for the DG (d= 1.73) and a small effect size for the SG (d= 0.30) as presented in Table 4.9. Groups were significantly different (p= 0.003). Post hoc analysis also revealed a significant difference between groups within the sprint trials (p= 0.006), which was also supported by the large effect size between groups when sprinting (d= 1.72). No post hoc significance was found between groups in relation to the distance pace trials (p= 0.907). Figure 4.46 indicates that the DG reached maximum left shoulder roll earlier (7.43%) than SG at sprint pace.

The time to maximum right shoulder roll was significantly different between paces (p= 0.030), with the SG and DG displaying a moderate (d= 0.61) and large effect size (d= 0.85) respectively. The groups were also found to differ significantly (p= 0.020), which was supported by the large effect sizes between the groups at both paces (Table 4.9). There was no significant pace-group interaction (p= 0.770). Figures 4.46 and 4.47 indicate that the SG took longer than the DG to obtain maximum right shoulder roll independent of the swim pace.

Time to maximum left hip roll was significantly different between paces (p< 0.001), which was supported by the large effect size for both groups across paces (Table 4.9). Both groups took longer to reach maximum left hip roll at distance pace by 14.23% (SG) and 13.38% (DG) relative to sprint swimming. No significant difference was found between groups (p= 0.840), and there was no significant pace-group interaction (p= 0.669).

Time to maximum right hip roll was significantly different between paces (p< 0.001), with the SG and DG taking 10.81% SC and 13.58% SC longer to reach the instant of maximum roll at distance than sprint pace. A large effect size was found between paces for both the SG (d= 1.39) and DG (d= 1.61). Moreover, post hoc analysis revealed a significant difference between paces within the DG (p= 0.0041), but the difference within the SG did not reach significance (p= 0.155). There was no significant difference between groups (p= 0.586) and no significant pace-group interaction (p= 0.623).

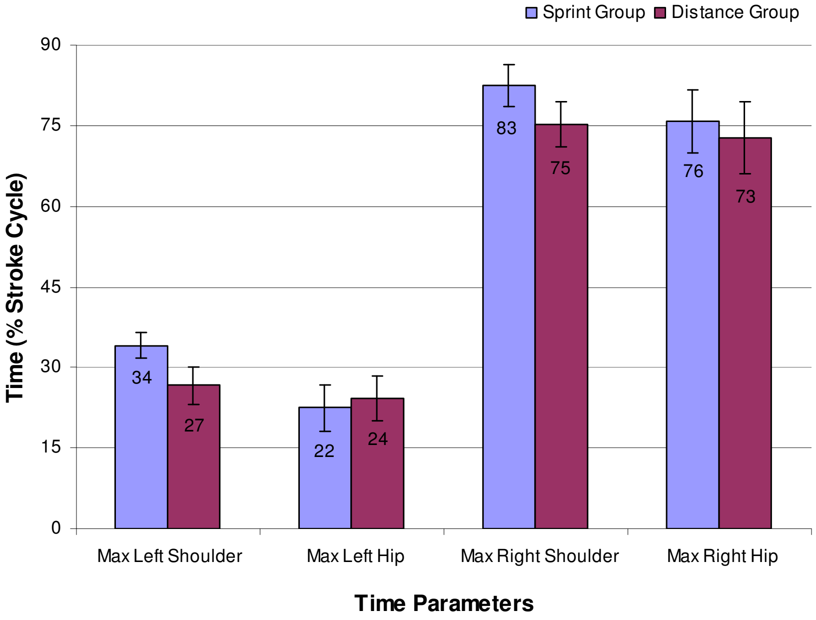


Figure 4.46: Time (%SC) to maximum shoulder and hip roll at sprint pace- SG vs. DG. Mean time data are indicated. Error bars represent 95% confidence interval of the true mean.

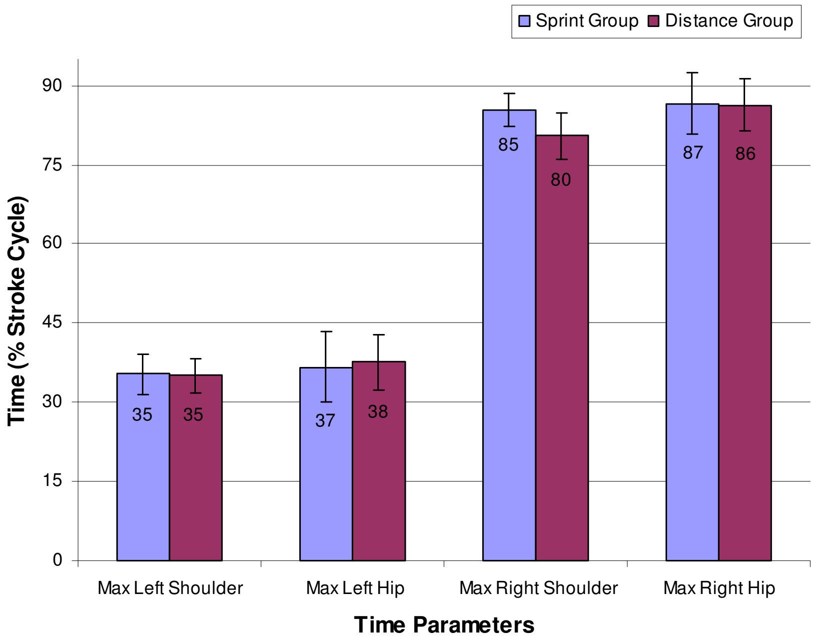


Figure 4.47: Time (%SC) to maximum shoulder and hip roll at distance pace- SG vs. DG. Mean time data are indicated. Error bars represent 95% confidence interval of the true mean.

4.3.4.3. Relationship between Shoulder and Hip Roll

4.3.4.3.1. Sprint Pace

The times to maximum left shoulder and hip roll were significantly different (p= 0.003) by 11.62% (SG) and 2.42% (DG) at sprint pace, with the maximum left hip roll obtained prior to the maximum left shoulder roll. The shoulder/hip-pace was significantly different for both the SG (p= 0.006) and DG (p= 0.039), meaning that one parameter changed more between the paces than the other parameter. Figures 4.48 and 4.49 indicate that the time to maximum left hip roll changed the most between paces. The shoulder/hip-group interaction was significant (p= 0.035). Post hoc analysis revealed a significant difference within the SG between paces (p= 0.0076) but not within the DG (p= 0.3812), meaning that the SG changed the timing between the left shoulder and left hip between paces more than the DG. Figure 4.48 indicates that the SG obtain maximum left hip roll prior to maximum roll of the left shoulder when sprinting, whereas at distance pace the left shoulder and hip roll simultaneously.

When sprinting, the difference in time to maximum right shoulder and hip roll approached significance (p= 0.069), with SG and DG tending to reach maximum right hip roll prior to the time of maximum right shoulder roll (Figures 4.48 and 4.49). The shoulder/hip-pace was significantly different for both the SG (p= 0.05) and DG (p= 0.06), meaning that one parameter changed more between the paces than the other parameter. Figures 4.48 - 4.49 indicate that the time to maximum right hip roll changed the most between paces.

4.3.4.3.2. Distance Pace

The times to maximum left shoulder and hip roll were not significantly different (p= 0.301) at distance pace, meaning that both shoulder and hip roll simultaneously to the left side. The time to maximum right shoulder and hip roll was significantly different (p= 0.02) at distance pace, with swimmers reaching maximum right shoulder roll prior to the time of maximum right hip roll. Post hoc analysis revealed a significant difference within the DG (p= 0.003) but not for the SG (p= 0.630). This indicates that the DG had a sequencing of right shoulder and right hip roll at distance pace, whereas the SG had a more simultaneous attainment of maximum right shoulder and hip roll (Figure 4.49).

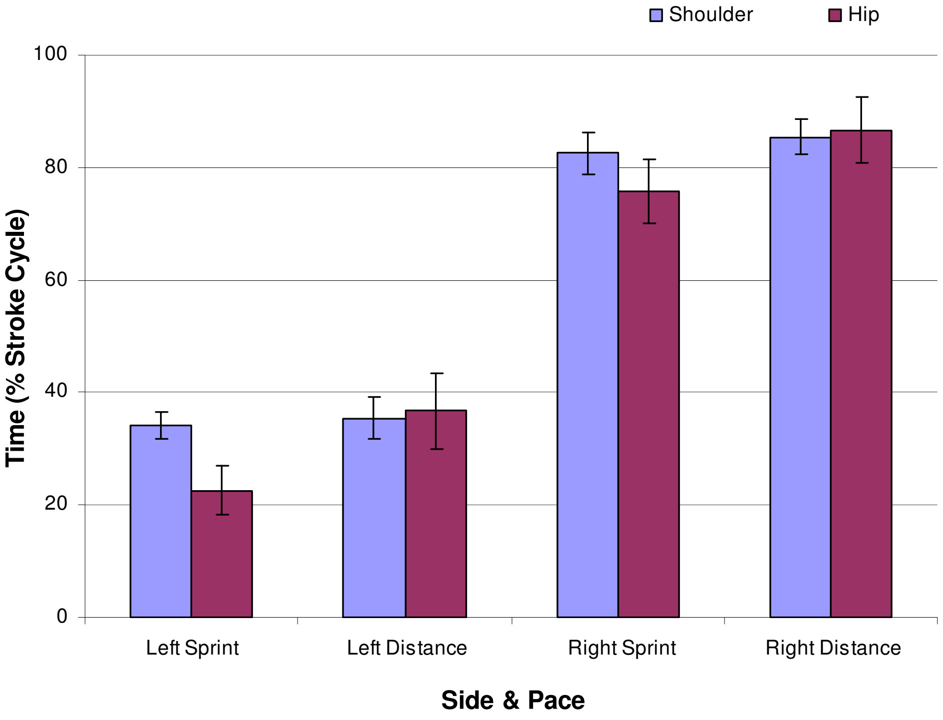


Figure 4.48: SG- Time (%SC) to maximum shoulder and hip roll for both sides at sprint and distance pace. Error bars represent 95% confidence interval of the true mean.

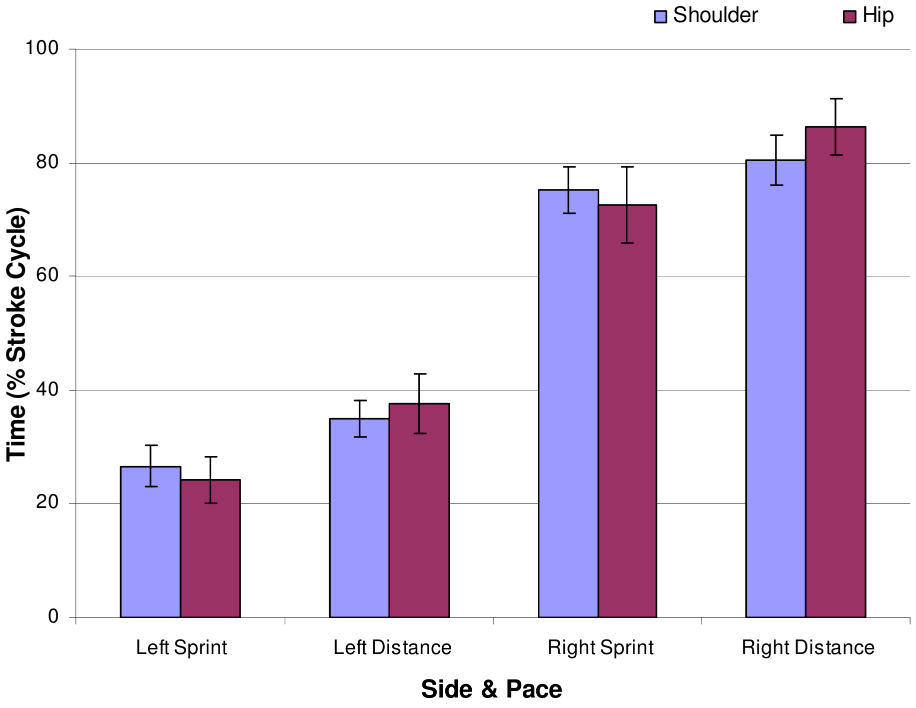


Figure 4.49: DG- Time (%SC) to maximum shoulder and hip roll for both sides at sprint and distance pace. Error bars represent 95% confidence interval of the true mean.

4.3.4.4. Total Shoulder & Hip Roll

Total shoulder roll was significantly different between paces (p= 0.001), with both SG (3.91deg) and DG (4.35deg) rolling more at distance than sprint pace (Figure 4.50). There was no significant difference between groups (p= 0.210), nor a significant pace-group interaction (p= 0.877).

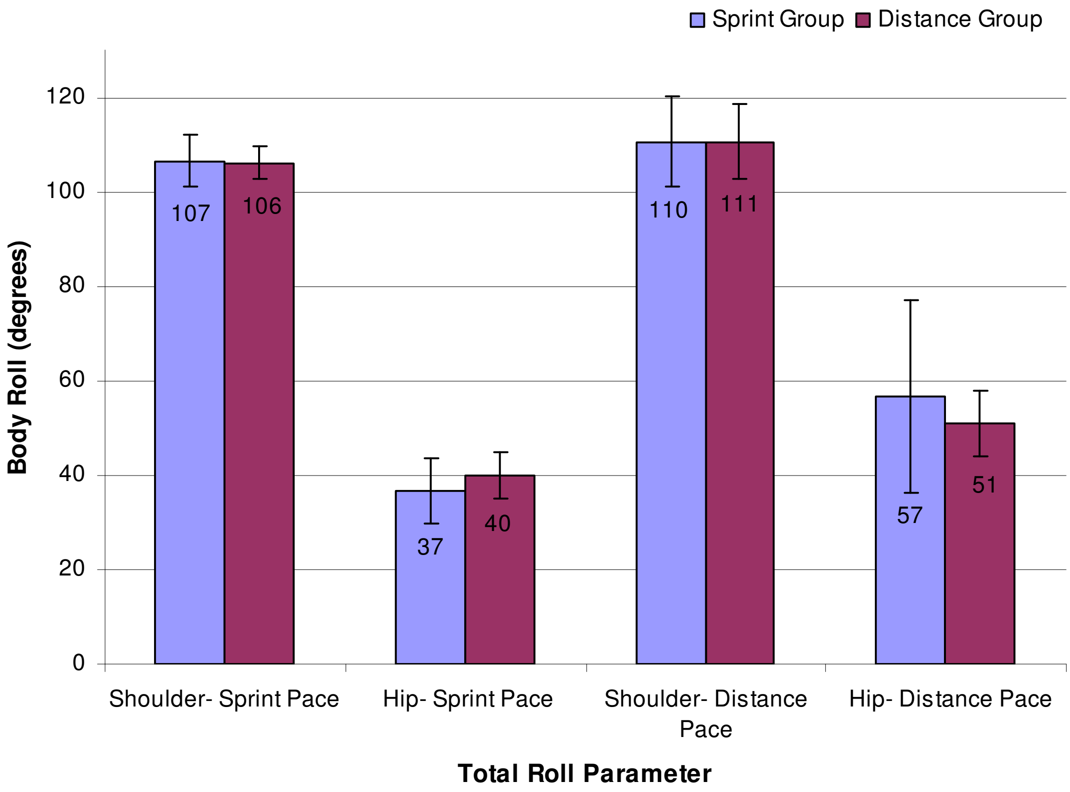


Figure 4.50: Total shoulder and hip roll- SG vs. DG at both paces. Mean total roll angle data are indicated. Error bars represent 95% confidence interval of the true mean.

Total hip roll was significantly different between paces (p= 0.001), with both groups rolling more at distance than sprint pace (by 19.92°-SG and 11.02°-DG). Post hoc analysis revealed a significant difference between paces within the DG (p= 0.0002) while the difference between paces within the SG approached significance (p= 0.029). The aforementioned result was supported by the large effect sizes across paces by both groups for the total hip roll (Table 4.9).

4.3.5. Kicking Vertical Range of Motion

Vertical displacement range of the left and right feet were compared for both groups and presented in Figures 4.51 and 4.52. The effect size data for all the foot vertical displacement data are presented in Table 4.10.

	Effect Size SG	*Effect Size DG*	*Effect Size Sprint*	*Effect Size Distance*
Left Foot Range	1.19	0.52	0.38	-0.58
Right Foot Range	1.01	0.60	0.48	-0.48
Sum Av Vertical Displacement	1.08	0.26	0.63	-0.62

Table 4.10: Effect size data for the vertical displacement range of both feet. The effect size between paces within the SG and DG are presented on the left side columns. The effect size between groups within the sprint and distance paces are presented on the right side columns.

The sum average of this variable is also presented, which is the combined sum of the left and right foot vertical displacement range throughout each kick. Since all swimmers displayed a six beat kick throughout each SC analysed (in both the sprint and distance events), the mean over these six values were represented as the sum average of the foot.

The difference in the left and right foot vertical displacement range between paces approached significance for the SG (p= 0.066) with the vertical displacement of each foot being greater at sprint than at distance pace. However, a large effect size was found within the SG in relation to the left and right foot vertical displacement changes across paces (Table 4.10). The large range within the 95% confidence interval, evident in Figure 4.51, prevented the difference from reaching statistical significance. There was no significant difference between paces with respect to the vertical displacement range of the left and right foot for the DG (p= 0.261) (Figure 4.52).

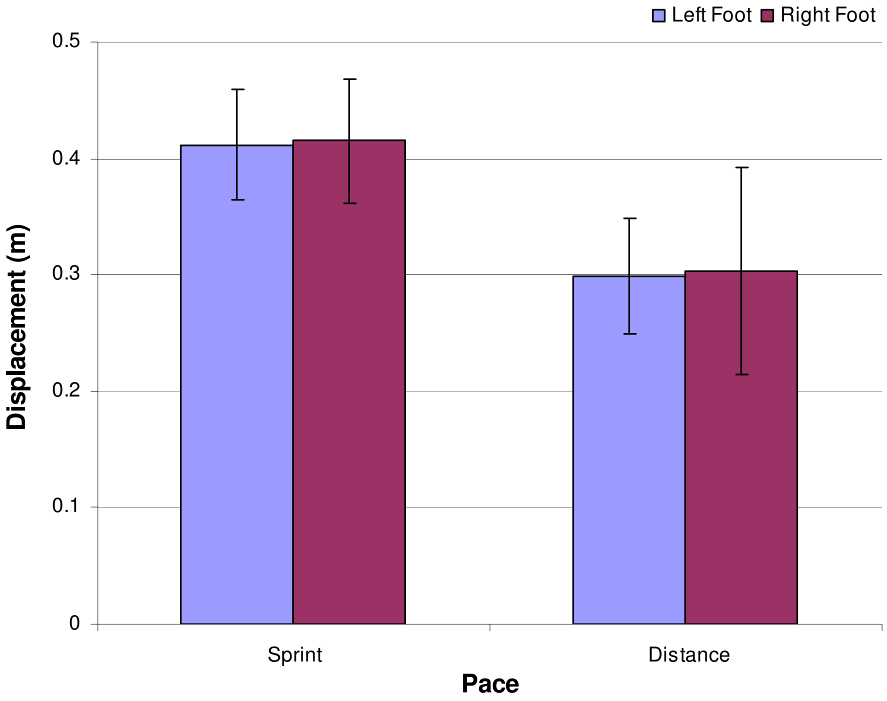


Figure 4.51: SG: left and right foot vertical displacement- sprint vs. distance pace. Error bars represent 95% confidence interval of the true mean.

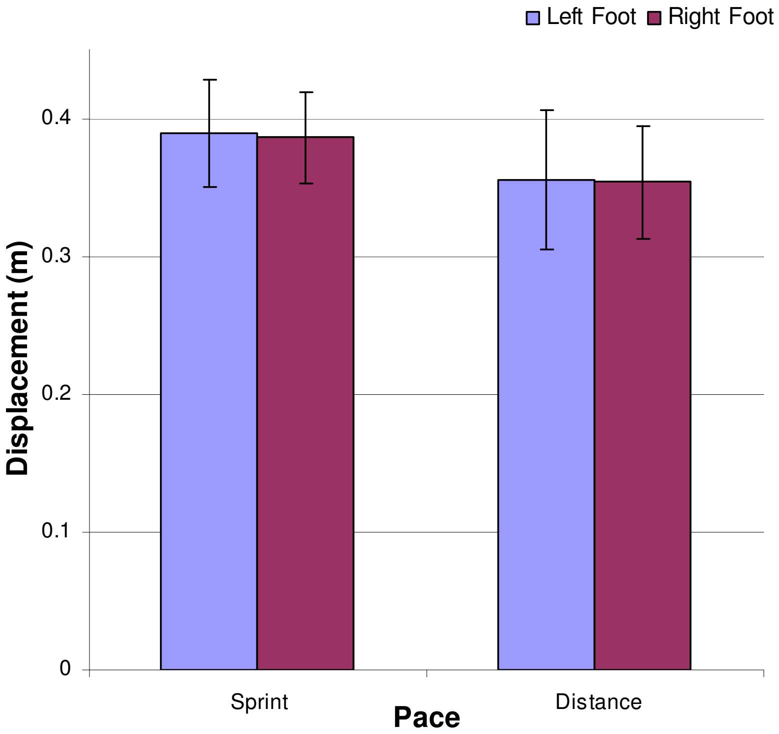


Figure 4.52: DG: left and right foot vertical displacement- sprint vs. distance pace. Error bars represent 95% confidence interval of the true mean.

The sum average of the foot vertical displacement was significantly different between paces (p= 0.039), but not between groups (p= 0.877), nor a significant pace-group interaction (p= 0.210). Table 4.10 indicates a large effect size between the paces within the SG (d= 1.08), and a moderate effect size between groups across both sprint (d= 0.63) and distance (d= 0.62) paces. SG and DG reduced the mean sum average foot vertical displacement by 0.11 m and 0.02 m respectively at distance than sprint pace. Figure 4.53 indicates that the SG reduced the foot displacement the most when distance swimming, but due to the large SD, this observation was not significant.

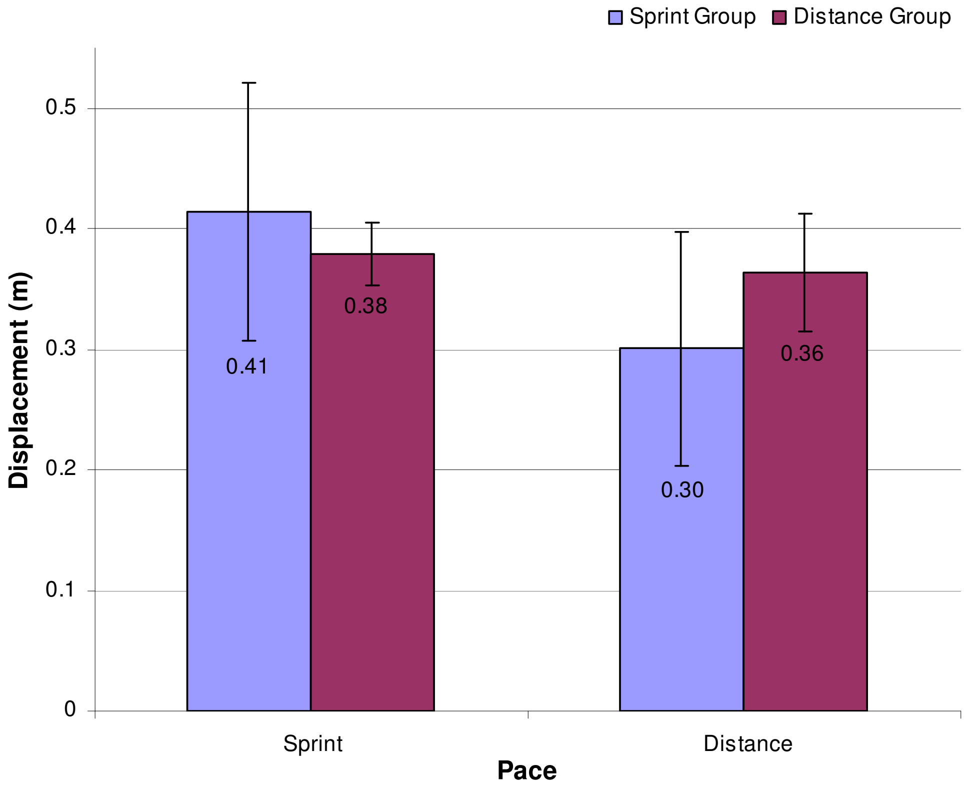


Figure 4.53: Sum average of the foot vertical displacement (m) - SG vs. DG between sprint and distance pace. Mean displacement data are indicated. Error bars represent 95% confidence interval of the true mean.

4.4. Kinetic Parameters

4.4.1. COM Horizontal Velocity Pattern

The AvV_{COMHor} velocity - normalised time profile for both groups is shown in Figure 4.54.

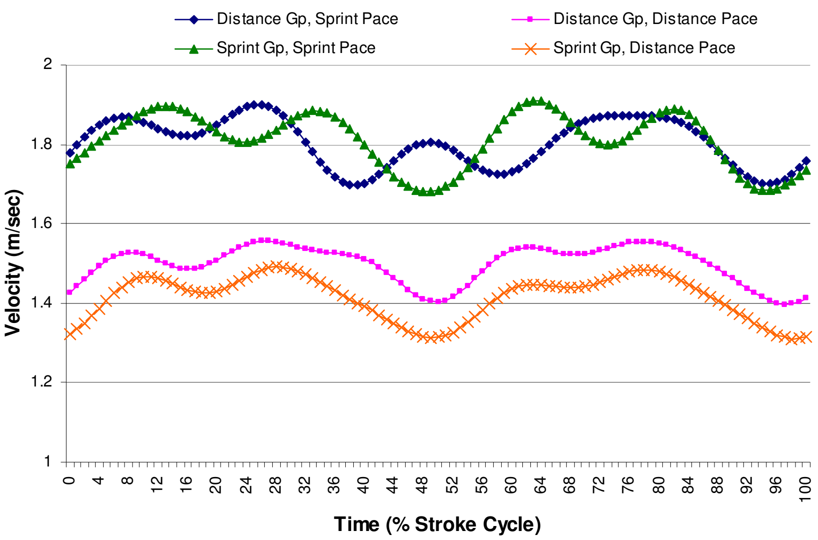


Figure 4.54: Mean horizontal velocity-normalised time profiles of the COM during one SC- SG vs. DG at sprint and distance pace. Each mean curve was the average across participants per group, with regards to this variable, which was calculated over three trials per participant (per pace).

Table 4.11 presents the effect size data for the COM horizontal velocity variables.

	Effect Size SG	*Effect Size DG*	*Effect Size Sprint*	*Effect Size Distance*
Average Velocity	6.14	6.00	0.17	-1.64
Maximum Velocity	5.20	4.06	0.26	-1.38
Minimum Velocity	4.14	2.66	0.00	-1.38
Range Velocity	2.39	1.45	2.32	4.72
Time to Max Velocity	0.23	-0.62	0.25	-0.62
Time to Min Velocity	0.25	-0.16	0.23	-0.62

Table 4.11: Effect size values for the COM horizontal velocity data. The effect size between paces within the SG and DG are presented on the left side columns. The effect size between groups within the sprint and distance paces are presented on the right side columns.

Both groups have similar velocity-normalised time profiles at sprint and distance pace (Figure 4.54). At the latter pace, the DG had a higher overall AvV_{COMHor} velocity-normalised time profile than the SG. A two peak velocity pattern, per arm stroke, is evident at both paces for both groups.

4.4.1.1. Average COM Horizontal Velocity

The higher AvV_{COMHor} at sprint than distance pace (by 0.40 $m\cdot s^{-1}$ and 0.30 $m\cdot s^{-1}$ for the SG and DG respectively) was significant ($p< 0.001$) (Figure 4.55), with a large effect size for both groups across paces (Table 4.11). Both the groups ($p= 0.071$) and the pace-group interaction ($p= 0.071$) approached significance at distance pace. Post hoc analysis revealed that the difference in AvV_{COMHor} between groups approached significance within the distance pace trials ($p= 0.015$) but not within the sprint pace trials ($p= 0.770$). Moreover, a large effect size was found between groups within the distance pace trials. It is evident that the DG maintained a greater AvV_{COMHor} at distance pace relative to the SG (Figure 4.55).

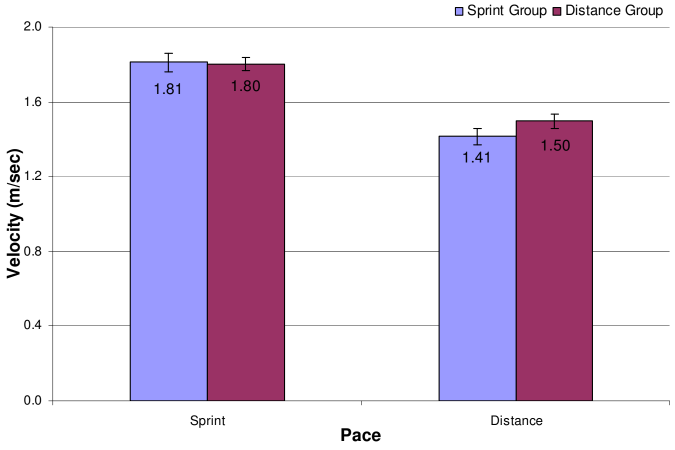


Figure 4.55: Average COM horizontal velocity- SG vs. DG at sprint and distance pace. Mean velocity measures are indicated. Error bars represent 95% confidence interval of the true mean.

4.4.1.2. Maximum COM Horizontal Velocity

The $MaxV_{COMHor}$ was significantly different ($p< 0.001$) between paces, with a greater $MaxV_{COMHor}$ at sprint (by 0.53 $m\cdot s^{-1}$- SG and 0.39 $m\cdot s^{-1}$- DG) than distance pace (Figure 4.56). A large effect size was found between paces for both groups (Table 4.11). There was no significant difference between groups ($p= 0.228$) nor a significant pace-group interaction ($p= 0.100$). However, post hoc analysis revealed that the difference between groups approached significance within the distance pace trials (p=

0.0196) and a large effect size (d= 1.38) was found within the distance pace trials between groups. No significance was found within the sprint pace trials (p= 0.6337) following post hoc analysis.

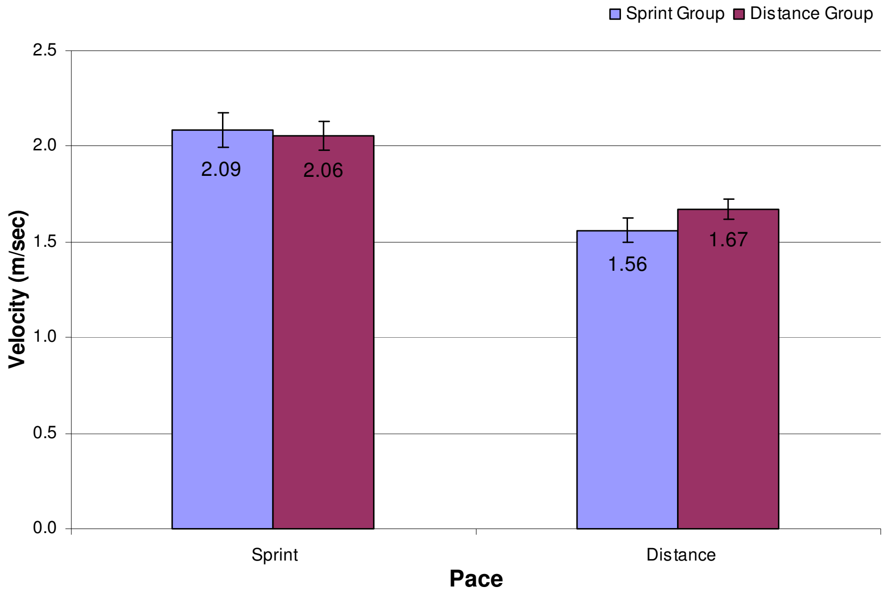


Figure 4.56: Maximum horizontal velocity of the COM- SG vs. DG at sprint and distance pace. Mean velocity measures are indicated. Error bars represent 95% confidence interval of the true mean.

4.4.1.3. Time to Maximum COM Horizontal Velocity

The time to MaxV$_{COMHor}$ was not significantly different between paces (p= 0.764), with the SG showing a small effect size (d= 0.23) and the DG a moderate effect (d= 0.62). No significant difference was found between groups (p= 0.750). There was no significant pace-group interaction (p= 0.339) (Figure 4.57). As indicated in the reliability section (4.1) the non-significant result is most likely due to the large SD with respect to this variable.

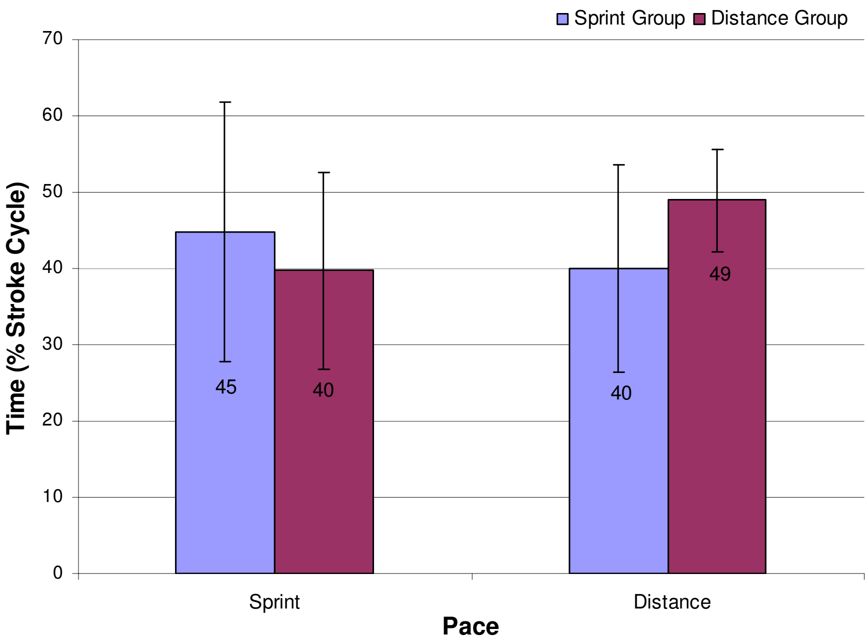


Figure 4.57: Time (%SC) to maximum COM horizontal velocity- SG vs. DG at sprint and distance pace. Mean velocity measures are indicated. Error bars represent 95% confidence interval of the true mean.

4.4.1.4. Minimum COM Horizontal Velocity

The MinV$_{COMHor}$ was significantly different between paces ($p< 0.001$), with a greater MinV$_{COMHor}$ at sprint than distance pace (by 0.27 m·s^{-1}- SG and 0.21 m·s^{-1}- DG). A large effect size was found between paces, for both SG ($d= 4.14$) and DG ($d= 2.66$), in relation to this variable. There was no significant difference between groups ($p= 0.280$), nor a significant pace-group interaction ($p= 0.263$). However, post hoc analysis revealed that the difference between groups approached significance within the distance pace trials ($p= 0.021$) but not within the sprint pace trials ($p= 0.995$). This was supported by the large effect size between groups within the distance pace trials ($d= 1.38$). Figure 4.58 indicates that SG displayed a lower MinV$_{COMHor}$ than the DG when distance swimming.

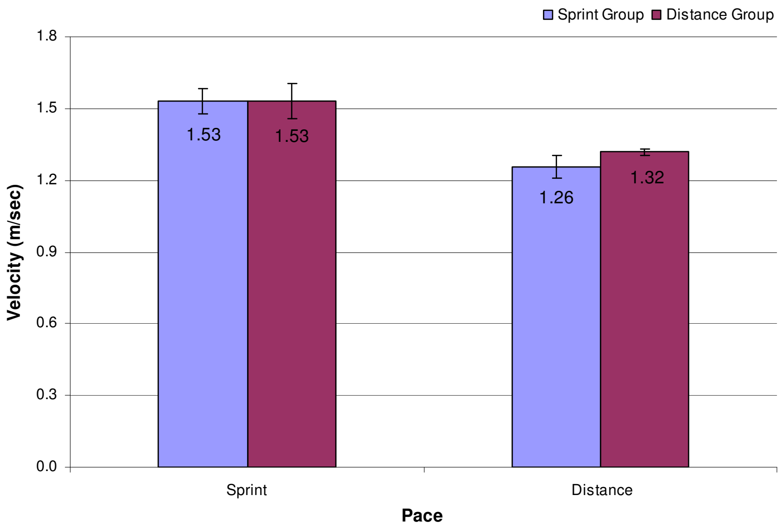


Figure 4.58: Minimum horizontal velocity of the COM- SG vs. DG at sprint and distance pace. Mean velocity measures are indicated. Error bars represent 95% confidence interval of the true mean.

4.4.1.5. Time to Minimum COM Horizontal Velocity

The time to MinV$_{COMHor}$ was not significantly different between paces (p= 0.867) (Figure 4.59), with both groups displaying a small effect size (Table 4.11). Groups did not differ significantly (p= 0.395), and there was no significant pace-group interaction (p= 0.593). However, as indicated in the reliability section (4.1) this variable is subject to large variability due to measurement error so it remains unclear as to whether there may be differences between paces and groups in this variable.

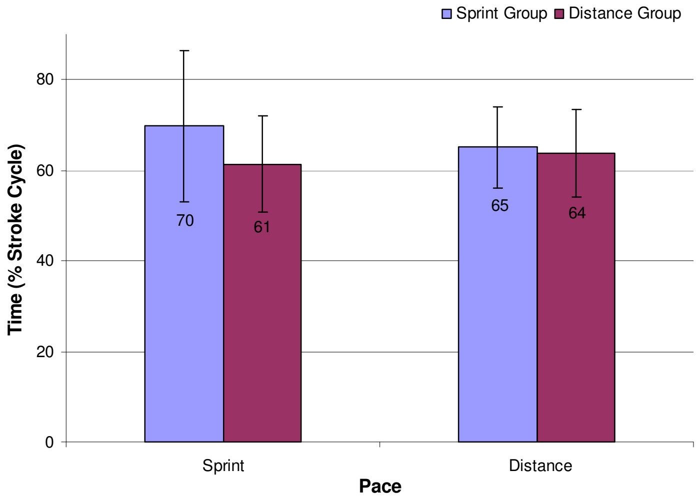


Figure 4.59: Time (%SC) to minimum COM horizontal velocity- SG vs. DG at sprint and distance pace. Mean time data are indicated. Error bars represent 95% confidence interval of the true mean.

4.4.1.6. Range COM Horizontal Velocity

The rangeV_{COMHor} was significantly different between paces ($p < 0.001$), with a greater rangeV_{COMHor} at sprint pace, by 0.25 $m \cdot s^{-1}$ (SG) and 0.17 $m \cdot s^{-1}$ (DG) relative to distance pace (Figure 4.60). Moreover, a large effect size was found between paces for both SG ($d = 2.39$) and DG ($d = 1.45$). There was no significance between groups ($p = 0.832$) nor a significant pace-group interaction ($p = 0.309$), despite a large effect size between the groups within both sprint ($d = 2.32$) and distance ($d = 4.72$) pace conditions.

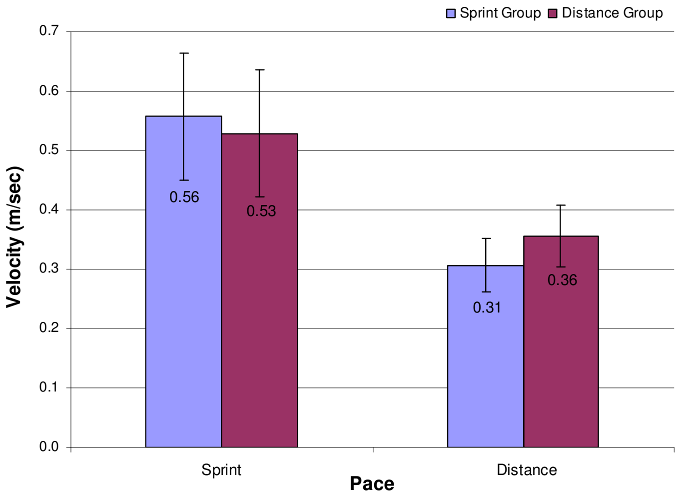


Figure 4.60: Range COM horizontal velocity- SG vs. DG at sprint and distance pace. Mean velocity range data are indicated. Error bars represent 95% confidence interval of the true mean.

4.4.2. Acceleration

The effect size COM acceleration data are presented in Table 4.12.

	Effect Size SG	*Effect Size DG*	*Effect Size Sprint*	*Effect Size Distance*
Max acceleration	2.43	1.39	0.60	-0.89
Time, max acceleration	1.52	-0.25	0.68	-1.34
Min acceleration	-2.23	-1.43	-0.49	0.92
Time, Min acceleration	-0.25	0.74	-1.01	-0.20
Range of acceleration	0.44	-1.16	0.44	-1.16

Table 4.12: Effect size data for the COM acceleration data. The effect size between paces within the SG and DG are presented on the left side columns. The effect size between groups within the sprint and distance paces are presented on the right side columns.

4.4.2.1. Maximum Acceleration

Max acc_{COM} was significantly different between paces ($p < 0.001$), with both the SG (by 4.76 $m \cdot s^{-2}$) and DG (by 2.28 $m \cdot s^{-2}$) obtaining a greater Max acc_{COM} at sprint than distance pace (Figure 4.61). Post hoc analysis revealed that the difference in Max acc_{COM} between paces was significant for the SG ($p = 0.0038$), and approached significance for the DG ($p = 0.0173$). Moreover, both groups displayed a large effect size across paces in relation to maximum acceleration (Table 4.12). There was no significant difference between groups ($p = 0.942$), despite a large effect size found between groups within the distance pace trials ($d = 0.89$). The pace-group interaction approached significance ($p = 0.069$), as the SG changed the magnitude of Max acc_{COM} more than the DG between paces.

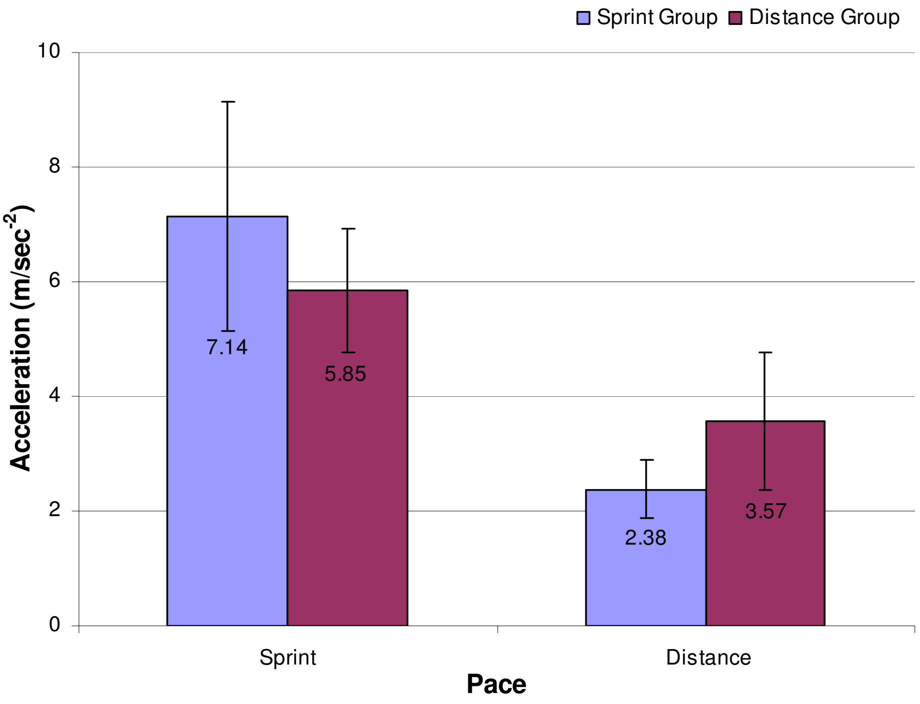


Figure 4.61: Maximum COM acceleration: SG vs. DG at sprint and distance pace. Mean acceleration data are presented. Error bars represent 95% confidence interval of the true mean.

4.4.2.2. Time to Maximum Acceleration

The difference in time to Max acc_{COM} between paces approached significance ($p = 0.079$), however the effect size data show that the SG had a large effect across paces ($d = 1.52$), whereas the DG had a small effect ($d = 0.25$). There was no significant difference between groups ($p = 0.659$), despite a large effect size between the groups within the distance pace trials (d= 1.34). The pace-group interaction was significant (p= 0.025) meaning that one group changed more than the other between paces. Figure 4.62 indicates that the SG changed more than the DG.

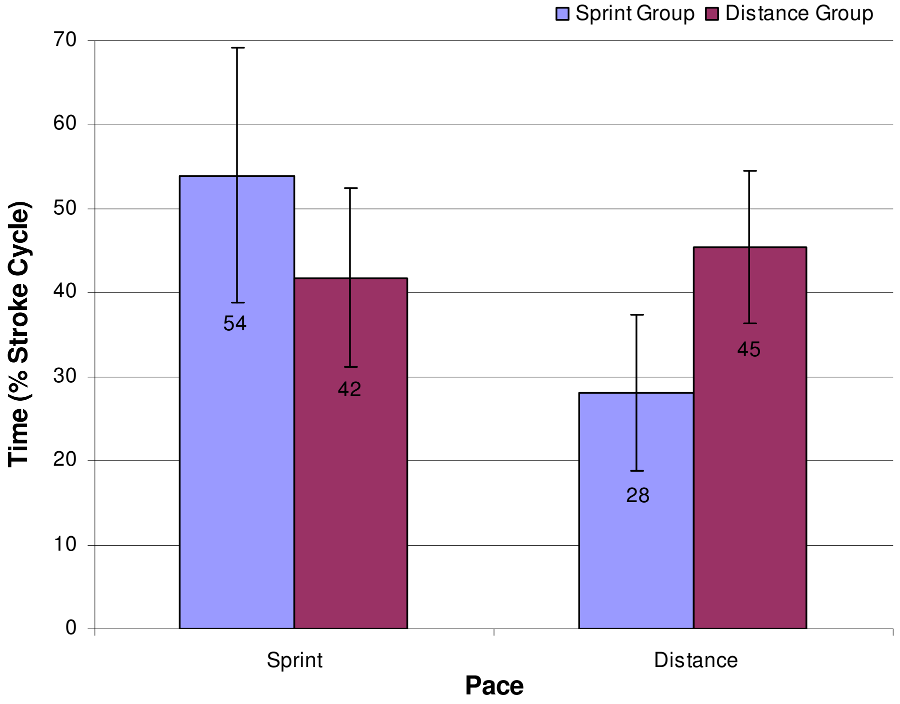


Figure 4.62: Time to maximum COM acceleration (%SC)- SG vs. DG swimmers at sprint and distance pace. Mean time data are presented. Error bars represent 95% confidence interval of the true mean.

4.4.2.3. Minimum Acceleration

The Min acc_{COM} was significantly different between paces ($p< 0.001$), with both groups obtaining a greater deceleration (by 4.56 $m \cdot s^{-2}$ (SG) and 2.25 $m \cdot s^{-2}$ (DG)) when sprinting than in distance swimming. Moreover both groups displayed a large effect across paces for the minimum acceleration variable (Table 4.12). There was no significant difference between groups (p= 0.899), despite a large effect size between groups within the distance pace trials (d= 0.92). The pace-group interaction approached significance (p= 0.076), suggesting that one group changed more than the other between paces. Figure 4.63 indicates that the SG changed the magnitude of Min acc_{COM} more than the DG between paces.

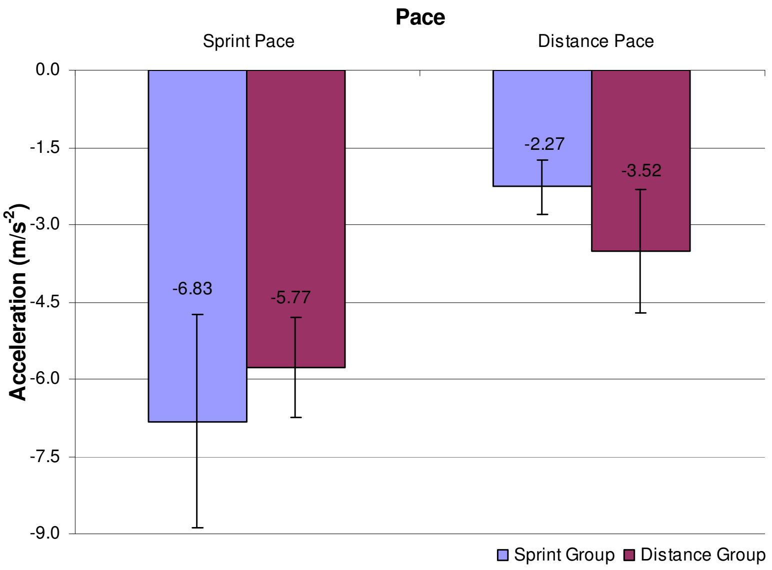


Figure 4.63: Minimum COM acceleration: SG vs. DG at sprint and distance paces. Mean acceleration data are presented. Error bars represent 95% confidence interval of the true mean.

4.4.2.4. Time to Minimum Acceleration

The time to Min acc$_{COM}$ was not significantly different between paces (p= 0.384) (Figure 4.64). A moderate effect size was found between paces within the DG (d= 0.74) and a small effect size within the SG (d= 0.25). Groups did not differ significantly (p= 0.243), despite a large effect size between groups within the sprint pace trials (d= 1.01). The pace-group interaction was not significant (p= 0.790). However, as indicated in the reliability section (4.1) the non-significant result is most likely due to the large SD with respect to this variable.

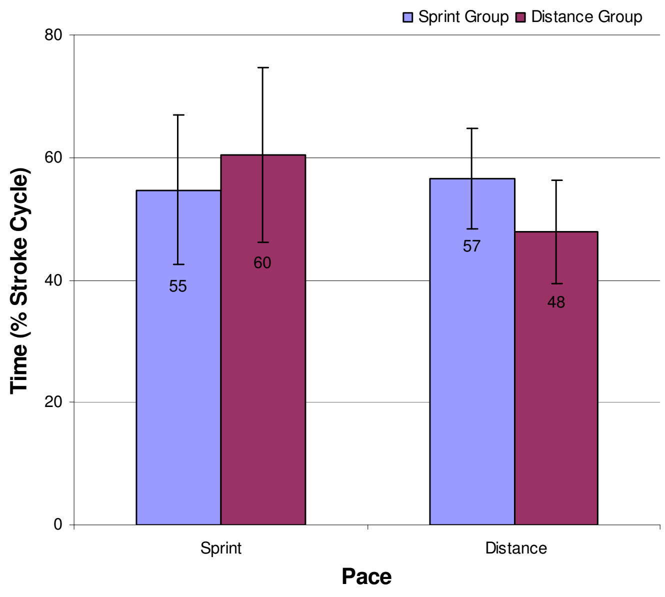


Figure 4.64: Time to maximum COM acceleration (%SC)- SG vs. DG at sprint and distance pace. Mean acceleration data are presented. Error bars represent 95% confidence interval of the true mean.

4.4.2.5. Range of Acceleration

The difference in range of acc_{COM} for both groups was significant between paces ($p< 0.001$), with a greater acc_{COM} range when sprinting (by 9.71 $m{\cdot}s^{-2}$ (SG) and 6.14 $m{\cdot}s^{-2}$ (DG)) than distance swimming (Figure 4.65). Both groups showed a large effect size across paces in relation to the range of acceleration (Table 4.12). There was no significant difference between groups ($p = 0.915$), nor a significant pace-group interaction ($p= 0.111$). Post hoc analysis revealed that the range of acc_{COM} between groups was significantly different within the distance pace trials ($p= 0.0002$), but not within the sprint pace trials ($p= 0.4060$). Moreover, a large effect size was found between the groups within the distance pace trials ($d= 1.16$), whereas a small effect size was found within the sprint trials ($d= 0.44$). Figure 4.65 indicates that the DG had a greater acc_{COM} range than the SG at distance pace (SG: 4.31 $m{\cdot}s^{-2}$ vs. DG: 5.95 $m{\cdot}s^{-2}$) despite the interaction not reaching statistical significance.

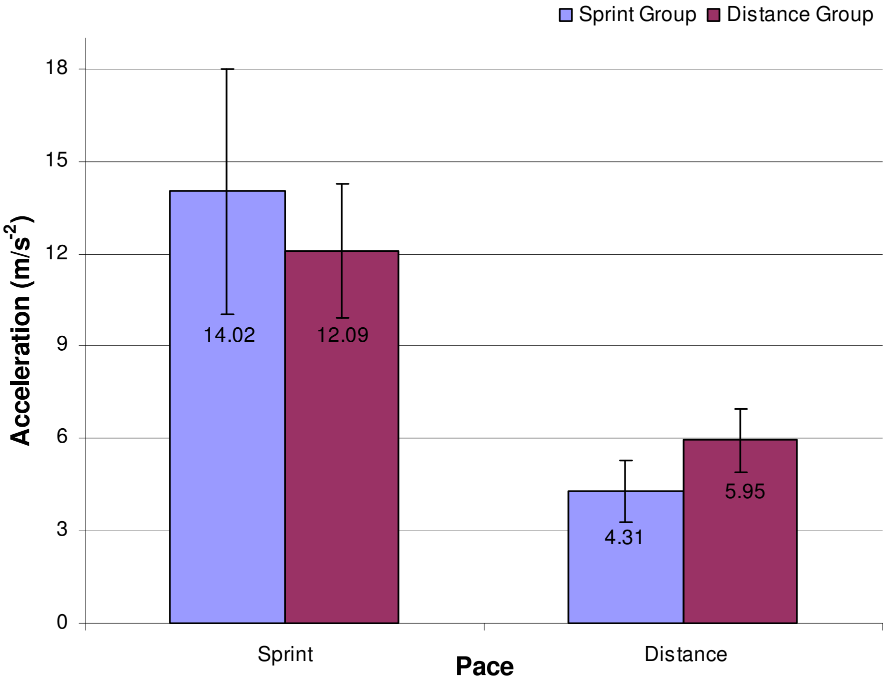


Figure 4.65: Acceleration range of the COM- SG vs. DG, at sprint and distance pace. Mean acceleration data are presented. Error bars represent 95% confidence interval of the true mean.

4.4.3. Force

The effect size data for the COM net force data are presented in Table 4.13, which shows that both groups displayed a large effect across paces with respect to the maximum and minimum COM net force. The time to maximum COM net force between paces was large within the SG (d= 1.52), but small within the DG (d= 0.37).

	Effect Size SG	*Effect Size DG*	*Effect Size Sprint*	*Effect Size Distance*
Max Force	2.60	1.75	0.48	-0.69
Time, Max Force	1.52	-0.37	0.73	-1.49
Min Force	-2.33	-1.78	-0.42	0.63

Table 4.13: Effect size values for the COM force data. The effect size between paces within the SG and DG are presented on the left side columns. The effect size between groups within the sprint and distance paces are presented on the right side columns.

4.4.3.1. Maximum COM Net Force

The Max force$_{COM}$ was significantly different between paces (p< 0.001), with SG and DG reducing the Max force$_{COM}$ by 357.36 N and 231.12 N respectively at distance than sprint pace (Figure 4.66). There was no significant difference between groups (p= 0.680) nor a significant pace-group interaction (p= 0.168), despite a moderate effect size between groups within the distance pace trials (d= 0.69).

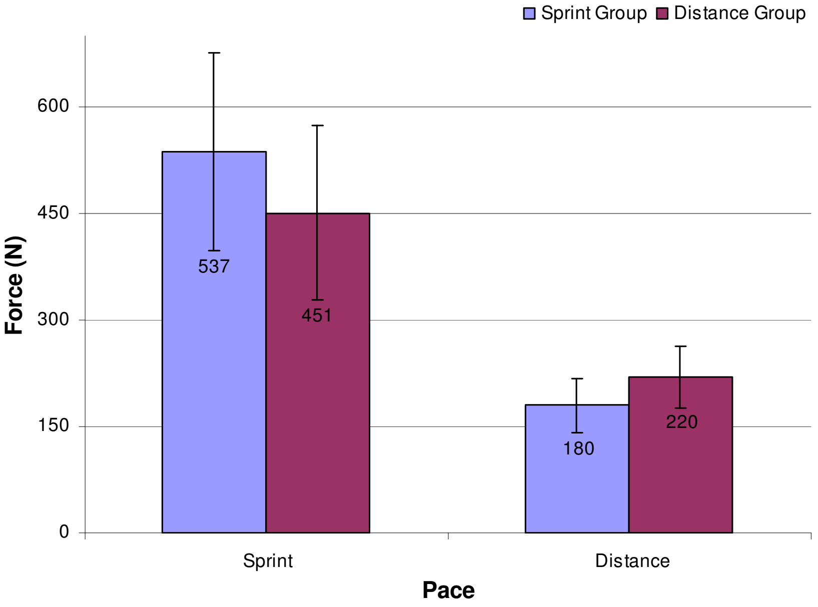


Figure 4.66: Maximum force$_{COM}$- SG vs. DG at sprint and distance pace. Mean force data are presented. Error bars represent 95% confidence interval of the true mean.

4.4.3.2. Time to Maximum Net Force

The time to Max force$_{COM}$ was not significantly different between paces (p= 0.098) (Figure 4.67), or groups (p= 0.736). The pace-group interaction was significant (p= 0.018) as the SG reached Max force$_{COM}$ 25.81% later at sprint pace (Figure 4.67). Post hoc analysis revealed that the difference in time to Max force$_{COM}$ between groups approached significance within the distance pace trials (p= 0.019), but not within the sprint pace trials (p= 0.179). The effect size data supported the post hoc analysis by finding a large effect size between the groups within the distance pace trials (d= 1.49). Figure 4.67 indicates that the DG obtained the Max force$_{COM}$ 17.53% later in the SC than the SG when distance swimming.

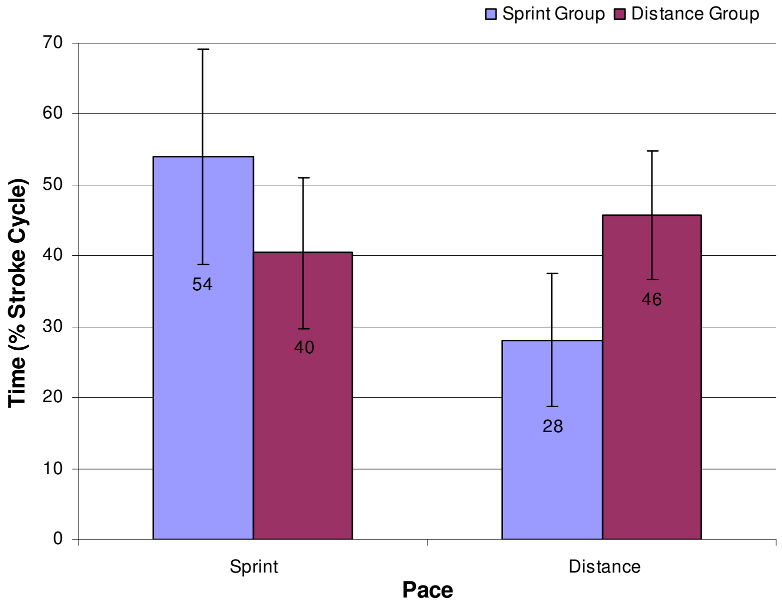


Figure 4.67: Time to maximum force$_{COM}$ (%SC) - SG vs. DG at sprint and distance pace. Mean time data are presented. Error bars represent 95% confidence interval of the true mean.

4.4.3.3. Minimum Net Force

The Min force$_{COM}$ was significantly different between paces ($p < 0.001$) (Figure 4.68), with both groups having a greater Min force$_{COM}$ when sprinting than when distance swimming. There was no significant difference between groups ($p = 0.819$) nor a significant pace-group interaction ($p = 0.155$).

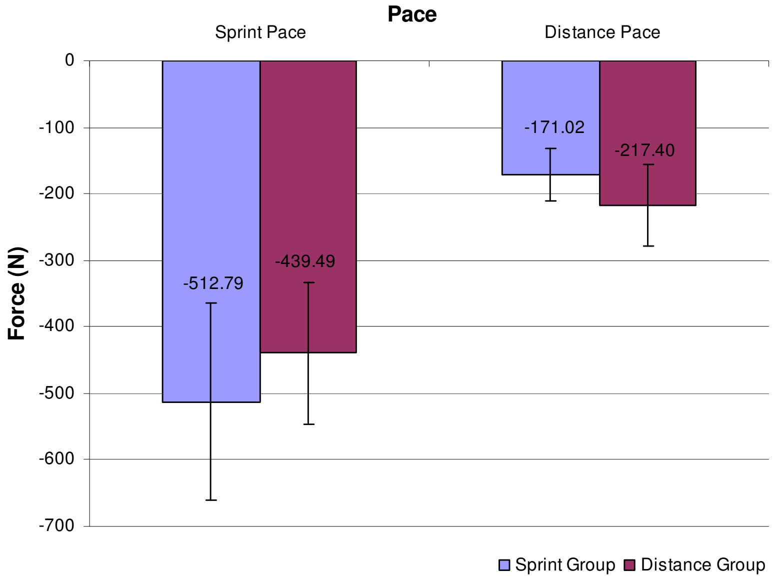
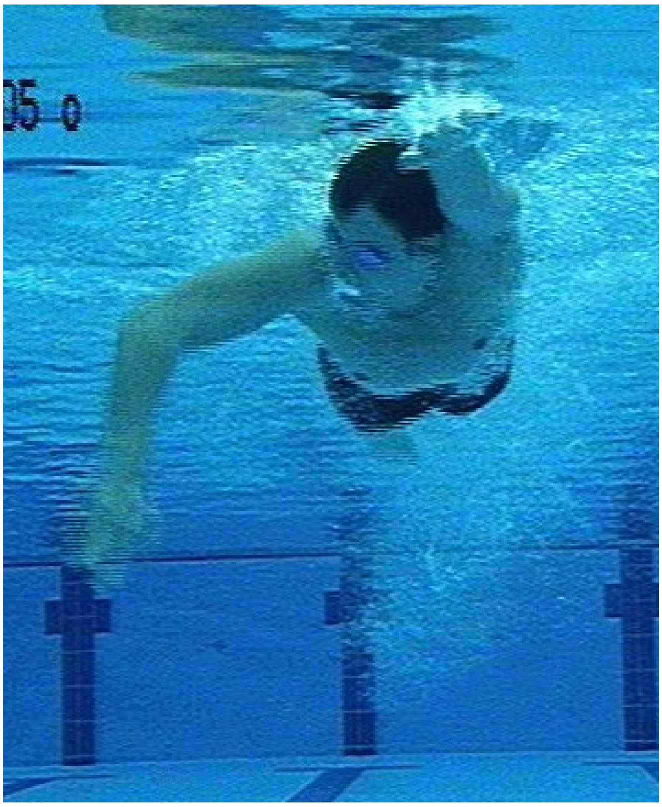


Figure 4.68: Minimum force$_{COM}$- SG vs. DG at sprint and distance pace. Mean force data are presented. Error bars represent 95% confidence interval of the true mean.

Chapter Five: Discussion



In the previous chapter, the results of this study were presented in relation to pace, group, and the interaction between pace and group. In this chapter the variables that were found to differ between the groups and paces are discussed. Moreover the kinematic and kinetic commonalities between groups, across sprint and distance pace are also discussed.

5.1. Are Sprint and Distance Swimmers Different From Each Other?

The primary purpose of this study was to investigate whether SG and DG differ in terms of kinematic and kinetic variables when swimming at similar velocities. This study revealed that these two groups are distinguishable with respect to the duration of the pull and push phases and the temporal sequencing of the shoulders and hips rolling. Differences between other variables approached significance between groups, indicating that with a larger sample, and/or increased number of trials, significant differences may be found. These variables were the V_{av}, AvV_{COMHor} and Max V_{COMHor}, Min V_{COMHor} and range acc_{COM} at distance pace. The differences between the groups in relation to the above variables are discussed subsequently.

One of the main differences between SG and DG was the different durations (%SC) spent within the pull and push phases. Researchers have previously suggested that skilled and non-skilled swimmers display different durations (%SC) within stroke phases due to the variation of hand velocity and/or acceleration within that particular phase, but have not taken into account the race specialisation of the swimmer (Chollet et al., 2000; Lerda and Cardelli, 2003). Although hand velocity and acceleration were not assessed in this study, they were examined post-analysis to ascertain whether the different durations of the pull and push phases between groups could be accounted for by the magnitude of these variables. With respect to the second hand entry, the DG spent longer in the pull phase than the SG. It was observed, that SG had a greater vertical acceleration (Figure 5.1) and horizontal velocity (Figure 5.2) of the hand during the pull phase which most likely contributed to the reduced duration (%SC) of this phase by the SG relative to the DG. This action does not appear to be advantageous in terms of the magnitude of net $force_{COM}$ during the pull phase which showed that the DG displayed a greater net force$_{COM}$ when sprinting than the SG (-1500 N vs. -1185 N).

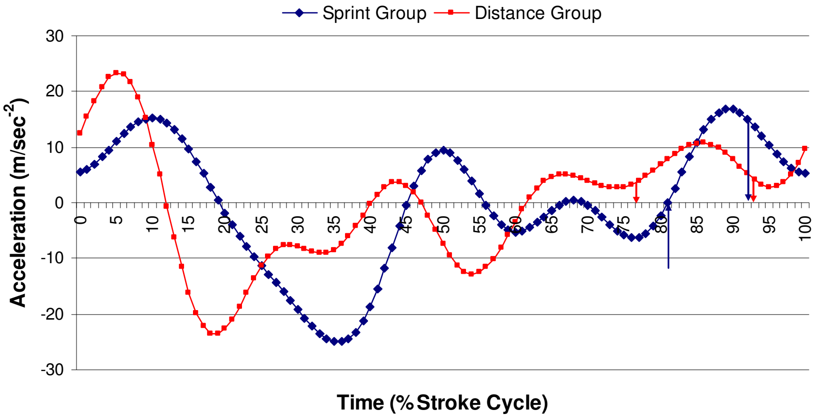


Figure 5.1: Vertical acceleration of the second hand entering the water during the stroke cycle, SG vs. DG, at sprint pace. The red and blue arrows indicate the beginning and end of the pull phase for sprint and distance swimmers respectively.

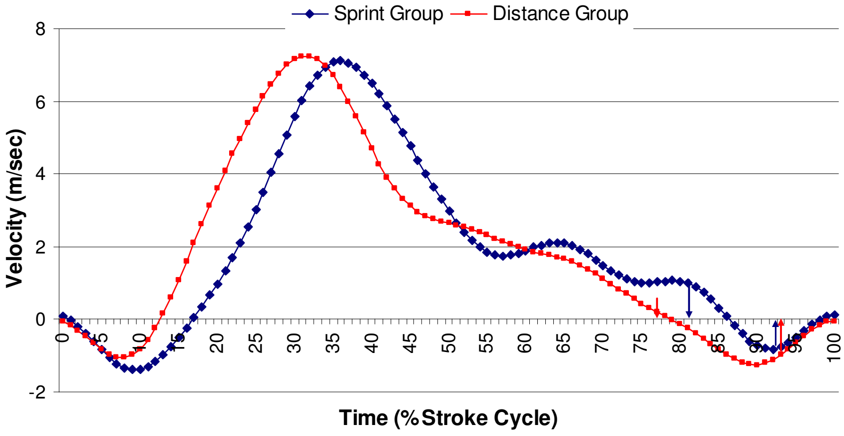


Figure 5.2: Horizontal velocity of the second hand entering the water during the stroke cycle, SG vs. DG, at sprint pace. The red and blue arrows indicate the beginning and end of the pull phase for sprint and distance swimmers respectively.

The difference between groups in the duration of the push phase approached significance with the SG having a shorter duration than the DG, particularly when sprinting. Figure 5.3 clearly indicates that SG had a greater magnitude of vertical acceleration of the hand during the push phase than the DG when sprinting. These results may be linked to the greater force$_{COM}$ of the SG than the DG at both sprint (801 N vs. 366 N) and distance pace (397 N vs. 367 N) within the push phase (Figure 5.4).

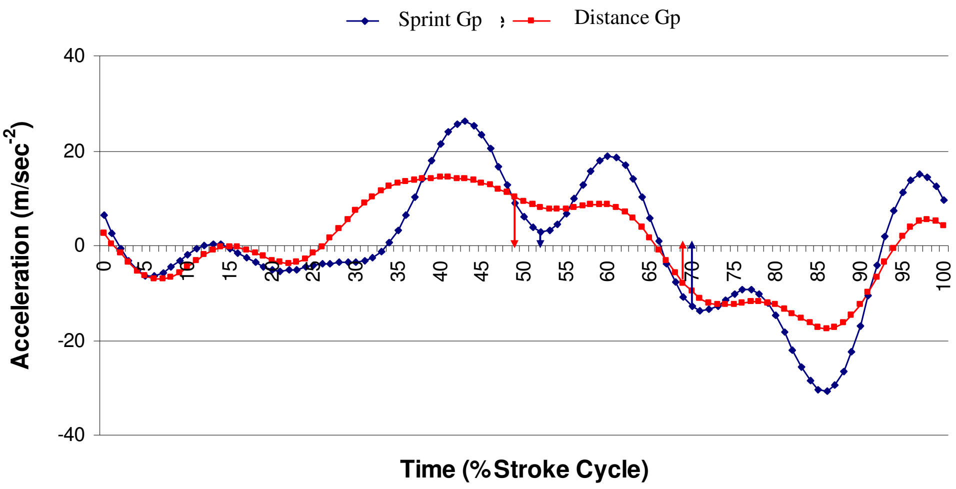


Figure 5.3: Vertical acceleration of the hand during the stroke cycle, SG vs. DG at sprint pace. The red and blue arrows indicate the beginning and end of the push phase for sprint and distance swimmers respectively.

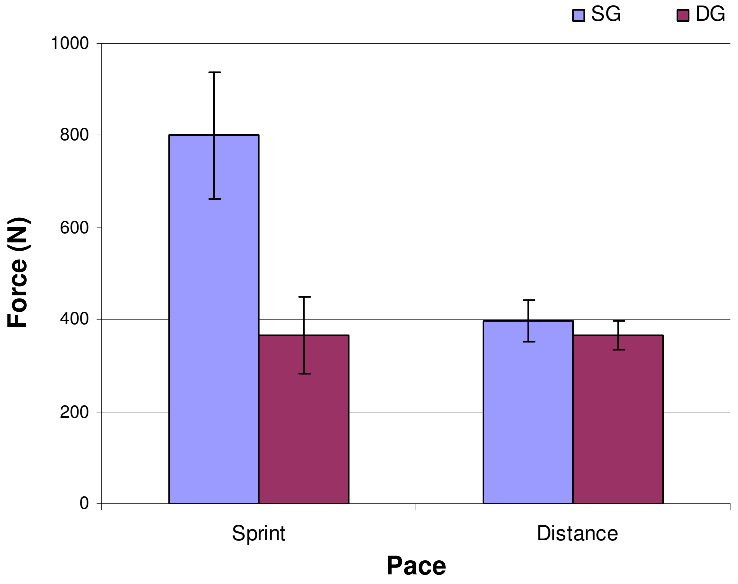


Figure 5.4: Mean net force during the push phase, SG vs. DG, at sprint and distance pace.

The results from this study support the current literature with respect to the duration of stroke phases being connected to the magnitude of hand velocity or acceleration within that particular phase. This connection has not been investigated in relation to swim groups in the previous literature. The SG spent less time (%SC) in the pull and push phases than the DG, which appears to be linked to a greater horizontal velocity and vertical acceleration of the hand within the pull phase, and a greater vertical acceleration of the hand during the push phase, relative to the DG.

No study has investigated the sequence order of the shoulders and hips rolling during a SC in swimming. This study revealed a different sequencing order of the shoulders and hips rolling between groups and between paces. When sprinting, the SG clearly led with the hips, as the shoulders followed. Although the DG showed this same trend, it was not as distinct as that of the SG, as supported by the significant shoulder/hip-group interaction in the results chapter. This altered sequencing of the shoulders and hips between groups when sprinting, may also explain the differences found between groups in terms of maximum shoulder roll (both sides) attainment, with the SG obtaining maximum shoulder roll later in the SC than the DG when sprinting (Figure 5.5), perhaps due to a greater time delay between the shoulder and hip segments rotating.

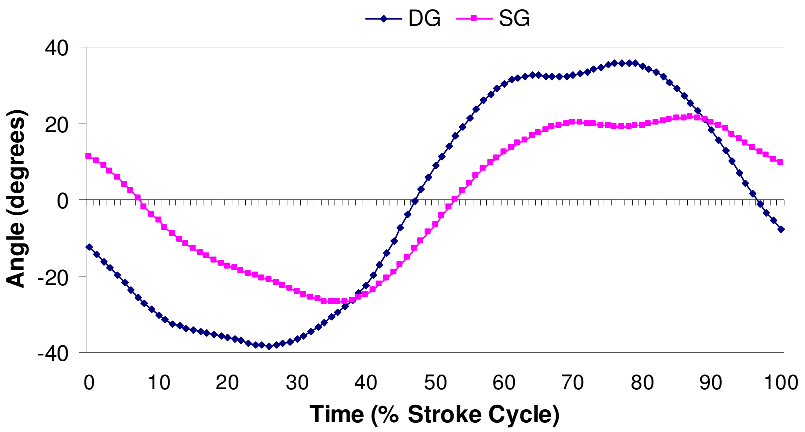


Figure 5.5: Mean shoulder roll angle for DG and SG at sprint pace. The difference in time of attainment of maximum roll to each side is evident.

At distance pace the SG rolled with the shoulders and hips simultaneously, whereas the DG displayed a distinct sequencing of the shoulders leading the hips throughout the SC. Consequently the shoulders and hips changed the temporal relationship between groups and paces. This finding may be related to other sports skills that also require humans to sequentially rotate the segments in order to execute the skill successfully, such as golf, baseball, tennis serve, javelin throw, and boxing. The primary objective of sequencing the body segments as a linked chain system in the previous sporting skills is to develop motion, or high speeds at the end of the link system for effective performance (Kreighbaum and Barthels, 1996). This is achieved by ordering the segment motion from the base segment, which is the most stable part of the system, to the free end; or from the proximal to distal end of the activity. In the case of the above activities, motion is generated by either the rotation of the trunk to initiate the movement or due to the application of ground reactive force. Failure to sequence a chain of segments progressively throughout the skill may result in an inadequate outcome at the end of the kinetic chain (Kreighbaum and Barthels, 1996). Prichard (1993) likened the skill of swimming to that of a baseball hitter, stating that the power originates from the hip rotation. However, in baseball, the sequential movement of the skill requires the player to rotate the segments about the hips, in addition to developing the necessary ground reaction force to initiate the movement, which is not possible in swimming. It is suggested that the kicking action of the legs in swimming may provide the torque to initiate the sequential motions throughout the body in order to effectively perform the cyclical motions of the arms (Yanai, 2001). Therefore, it is proposed that the flow of motion, or energy wave, travels from the bottom to the top of the swimmer, as is the case in many other sports. Although not statistically significant due to the large standard deviations, it is obvious that the SG displayed a greater vertical displacement of the feet relative to the DG when sprinting, and vice versa at distance pace. These observed differences in kicking action between the groups may explain the varied sequencing pattern of the shoulders and hips between the SG and DG. In conclusion, it was found that SG and DG sequence the rolling of the shoulders and hips in a different manner at both sprint and distance pace.

However, further investigation is required to advance the understanding of the shoulder and hip roll relationship. It would be especially interesting to analyse the different techniques used by the groups in their chosen events to investigate any energy wave properties. Computational fluid dynamics (CFD), which is one of the branches of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows, may provide a useful tool to examine the effect of water flow surrounding the trunk segment to identify why swimmers are sequencing their actions in this way.

The difference in V*av* approached significance between the groups at distance pace. Although not statistically significant, the greater ROM of the leg kick and higher SF by the DG relative to the SG, may have contributed to the greater maintenance of V_{av}

by the DG. The ability to swim fast with a higher SF has been linked to the maintenance of adequate neural activation to the working muscles (Hay, 1993; Keskinen and Komi, 1993). It is therefore suggested that the DG had a greater capacity to sustain effective contractibility of the muscles at distance pace than the SG. Additionally the greater contribution of the leg action by the DG at distance pace would have served as an extra source of propulsion to the swimming motion in comparison to the SG, resulting in a greater V_{av} maintenance.

Similar to the differences between groups with respect to the duration of stroke phases, the higher average and maximum V_{COMhor} of the DG, than the SG, when distance swimming may also be linked to the magnitude of hand velocity. Figure 5.6 indicates that the DG display a faster hand resultant velocity throughout the SC than the SG.

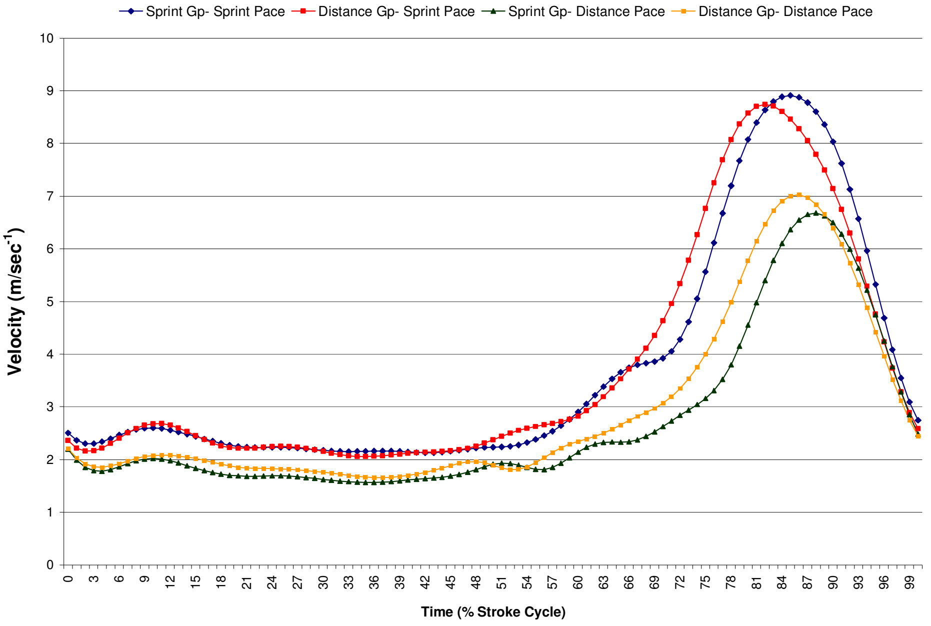


Figure 5.6: Hand resultant velocity: sprint vs. distance pace for both groups

The greater magnitude of deceleration (Min V_{COMhor}) of the DG relative to the SG at distance pace is most likely due to the effect of wave drag. Since wave drag is proportionally related to the swim speed, due to the greater AvV_{COMhor} by the DG relative to the SG throughout the SC, the magnitude of wave drag would act more strongly on the DG than the SG, resulting in a greater deceleration of the DG.

5.1.1. Summary of Differences between Groups.

This study revealed that SG and DG do not differ over a broad range of variables as suggested in the literature. The main differences between the groups were reasoned to be due to the differences in velocity or acceleration of the hand within the stroke phases, as well as the relative timing between the arms. An exciting difference between the groups was found with regard to the sequencing order of the shoulders and hips at both sprint and distance pace, which was speculated to be controlled by the magnitude of the leg action, but requires further examination.

5.2. Do the Groups Change Between Paces?

The second objective of this thesis was to investigate whether SG and DG adapt their race parameters, stroke kinematics and kinetics between sprint and distance pace. The aim of obtaining this knowledge is to understand why and how swimmers adjust their stroke characteristics between paces, as the current literature relating to this question is limited. This study revealed that many variables changed in terms of magnitude and the temporal aspect between the two paces for both groups, which are discussed subsequently.

The main change between paces with respect to the race parameters is that sprint swimming is characterised by a significantly greater V_{av}, SF, SI, and reduced SL, compared to distance swimming for both groups. Maximum V_{COMhor}, acc_{COM} and $force_{COM}$, were also significantly greater when sprinting than distance swimming. The greater magnitudes of these variables when sprinting is expected due to the much lower requirement to conserve energy or implement a pacing strategy, as is the case when distance swimming. All swimmers demonstrated a longer SL at distance pace concomitant with a reduced V_{av}, SF and SI. These adaptations are made automatically to yield an energy efficient stroke, as energy expenditure of a muscle cubes with the speed of muscle contraction and thus acts to delay the onset of acidosis as a by-product of a high SF (Maglischo, 2003). The fact that sprinting was characterised by a high SF and low SL, whilst distance swimming was exemplified by longer SL and reduced SF, further reiterates the negative relationship between SF and SL as reported in the literature (Arellano et al., 1994; Pelayo et al., 1996; Keskinen and Komi, 1993; Maglischo, 2003).

The greater magnitude of the V$_{COMhor}$ when sprinting, was due to the propulsive actions within the entry and push phases, relative to the pull, hand exit and recovery phases by both groups (Figure 5.7 and 5.8).

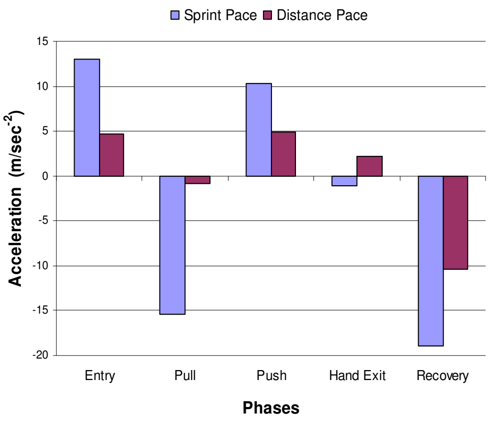


Figure 5.7: SG- mean acc$_{COM}$ during each stroke phase throughout the SC, at sprint and distance pace.

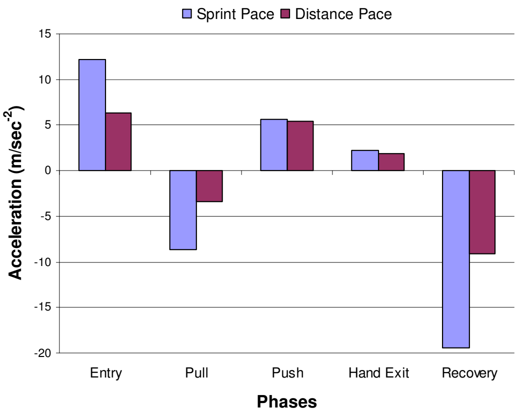


Figure 5.8: DG- mean acc$_{COM}$ during each stroke phase throughout the SC, at sprint and distance pace.

The propulsion generated during the entry phase is most likely due to the activities of the opposing arm, which relative to the entering arm was positioned in the latter portion of the push phase or at hand exit. Indeed, researchers have indicated that the hand achieves maximal velocity (Counsilman, 1981; Costill et al., 1992; Rouard et al., 1996; Monteil et al., 1996; Maglischo, 2003) and force production during the push phase (Schleihauf, 1982; Schleihauf et al., 1983; Cappaert et al., 1995; Monteil et al., 1996; Rouard et al., 1996; Cappaert, 1998), which would positively influence the COM. This study also revealed that maximum V$_{COMhor}$, acc$_{COM}$ and force$_{COM}$ occurred within the push phase, irrespective of swim velocity. This is in agreement with Maglischo et al. (1989), Rouard et al. (1996), Keskinen and Keskinen, (1997), Cappaert (1998) and Maglischo (2003), who all reported that maximum propulsion occurs during the push phase irrespective of the swim velocity.

Figure 5.6 clearly indicates that the hand speed changes between paces, with the hand travelling faster during the sprint trials than the distance trials. The advantage of a faster hand speed throughout the SC when sprinting, is due to the exponential relationship between hand speed and force. Doubling the speed yields a fourfold increase in force, if using the same stroke mechanics (Counsilman, 1973). Because the SF values in this study were 71-75% higher at sprint pace for both groups, swimmers applied more force when sprinting than distance swimming. This is manifested by the greater magnitude of acceleration in the entry and push phases as described previously.

All swimmers experienced greater resistance, in terms of a lower V_{COMhor}, and a greater Min acc_{COM} (deceleration) and Min net $force_{COM}$ (resistive force) when sprinting than distance swimming. This is most likely due to the effect of wave drag, in the form of a bow wave, acting on the swimmer. It is known that wave drag is proportional to the cube of the swimming velocity (Voronstov and Rumyantsev, 2000). Therefore, this retarding effect becomes more significant when sprinting than swimming at a distance pace and consequently acts as a limiting factor to forward propulsion. Figures 5.7 and 5.8 illustrate that maximum deceleration occurs within the pull and recovery phases. The implications of this result in terms of stroke kinematics are discussed subsequently.

Neither group adjusted the magnitude of maximum vertical and lateral displacement of the upper limbs between paces as suggested in the literature. However, the time that these variables occurred within the SC did change between paces. Maximum vertical displacement of the finger occurred approximately 10% later within the SC at distance than sprint pace for both groups. It is suggested that this result was a consequence of the prolonged entry phase (SG-9.05%, DG- 10.37%) when distance swimming compared to sprinting. Moreover, it was found that maximum vertical displacement occurred during the pull phase (middle of) for all swimmers which is in agreement with Cappaert et al. (1995).

Maximum finger lateral displacement occurred 20% and 2% later in the SC for SG and DG respectively at distance than sprint pace. This result was not a consequence of a prolonged entry phase due to the fact that the duration of the latter was increased by 10% when swimming at distance pace. To provide a better understanding Table 5.1 identifies the stroke phase that corresponds to maximum finger lateral displacement.

The SG obtained maximum lateral displacement in the pull phase when sprinting, which is in agreement with several authors (Colwin, 1969; Maglischo, 2003). Therefore, the maximum lateral motions of the upper limbs (which are regarded as non-propulsive in the literature) may explain why the SG exhibit a greater COM deceleration within this phase compared to the DG, when sprinting (-15.39 $m \cdot s^{-2}$ vs. -8.6 $m \cdot s^{-2}$).

	Sprint Pace	*Distance Pace*
Sprint Group	Pull	Push
Distance Group	Push	Push

Table 5.1: Corresponding phases to maximum lateral displacement of the finger.

The time to maximum lateral displacement of the finger occurred in the push phase for the DG at both paces and for the SG at distance pace. In most cases, this occurred prior to the initiation of the recovery phase. This indicates that the hand is furthest (laterally), from the COM during the latter portion of the push phase. These findings suggest that throughout the SC, swimmers tend to position the upper limbs in close proximity to the axis in the direction of swimming passing through the COM until the latter portion of the push phase, perhaps in preparation for the hand exiting the water. In doing so, the swimmer reduces the torques about the vertical axis that tend to rotate the swimmer and increase drag. Therefore, all swimmers change the temporal aspects of attaining the maximum vertical displacement of the finger between paces, primarily due to the knock-on effect of a prolonged entry phase at distance than sprint pace. The SG changed the maximum lateral displacement of the finger the most between paces perhaps due to the energy requirements of the race distance. These above changes influenced the acceleration characteristics of the COM.

Initially, it was proposed that the ‘maximum’ aspect of the stroke trajectory would provide useful information with regard to the vertical and lateral aspects of the stroke pattern. However, this was reassessed due to the results obtained and the average vertical displacement of the finger examined post analysis (Figure 5.9). This variable changed between paces ($p = 0.013$), but not significantly between groups ($p = 0.307$). All swimmers increased the average stroke depth of the hand when distance swimming compared to sprinting, which is contrary to all assumptions and predictions made in the literature. The difference in the range of lateral displacement of the finger between paces approached significance, with the majority of participants increasing this range at distance pace. As the elbow angle magnitude has previously been related to the stroke depth (Cappaert, 1998), this aspect was examined. However, no change was found in relation to the magnitude of the elbow angle variables between paces, with the exception of the end back elbow angle, which was smaller at distance pace and thus not likely to influence the stroke depth or stroke width magnitude. Because upper limb displacement has been related to the magnitude of body roll in the literature (Lui et al., 1993; Hay et al., 1993; Payton and Mullineaux, 1996), it is reasoned that the increased magnitude of shoulder and hip roll at distance pace, accounts for the increased magnitude of average vertical and lateral range displacement of the finger for all swimmers when distance swimming than sprinting. That is, shoulder and hip roll appear to influence the magnitude of average vertical and lateral range displacement of the finger between paces for both groups.

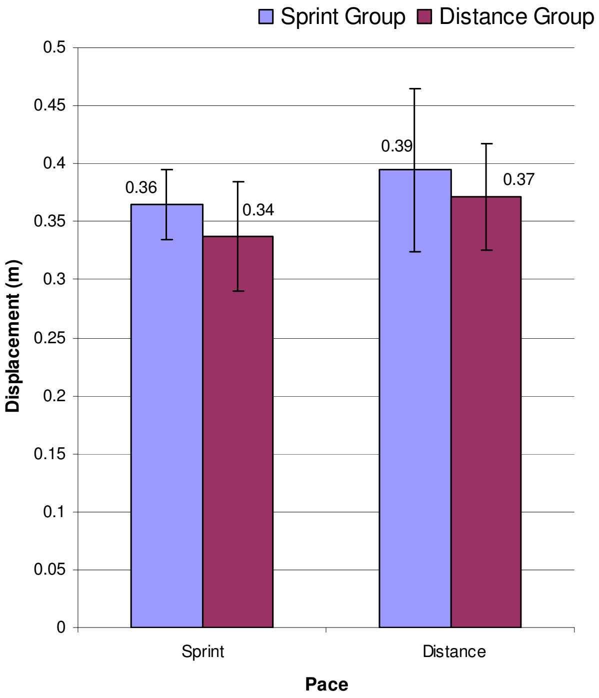


Figure 5.9: Average vertical displacement of the finger throughout the underwater stroke phase: SG vs. DG.

Many authors have explained the purpose of maximally extending the elbow during the entry phase in terms of improving the hydrodynamic position in the water whilst applying propulsive force with the opposing arm at distance pace (Costill et al., 1992; Voronstov and Rumyantsev, 2000; Millet et al., 2002; Lerda and Cardelli, 2003; Maglischo, 2003; Seifert et al., 2007a). Alternatively sprint swimming has been characterised in the literature as flexing the elbow rapidly after entry in order to make the catch earlier and apply propulsive forces for a longer period as a proportion of the SC (Colwin, 1969; Voronstov and Rumyantsev, 2000). This variable has not been investigated quantitatively in the literature in relation to swim velocity or swim group. One may have predicted that the 10% longer period in the entry phase when distance swimming would facilitate a greater elbow extension. It was therefore surprising to find that maximum right elbow angle during the entry phase was greater when sprinting than distance swimming for both groups. However, Deschodt et al. (1999) reported that the contribution of the leg-kick when sprinting significantly alters the wrist kinematics in the forward direction. The greater foot vertical displacement range in this study when sprinting, by both groups, may have influenced the greater forward extension of the right elbow angle after entry. Moreover, the fact that the majority of swimmers were right hand dominant may have resulted in the difference between the left and right side.

Researchers have not presently investigated whether the elbow angle changes between paces with respect to SG and DG. This study revealed that the magnitude of both the end back elbow angle and the range of elbow angle within the push phase changed between paces for both groups. The end back elbow angle is a measure of the elbow extension at the end of, what is regarded as, the most propulsive phase of the underwater SC. Both groups reduced the magnitude of the elbow angle at the end back event when distance swimming than sprinting by approximately 7°. The elbow angle range during the push phase was also reduced by 5.71° (SG) and 7.98° (DG) when distance swimming than sprinting. These adaptations appear to have influenced the kinetic aspects of the SC. Both SG and DG had a greater net force$_{COM}$ during the push phase when sprinting (SG- 800.59 N; DG- 366.28 N) as opposed to distance swimming (SG- 368.20 N; DG- 282.95 N). The acc$_{COM}$ data support the latter, showing a greater acceleration during the push phase when sprinting (SG- 10.35 $m{\cdot}s^{-2}$; DG- 5.62 $m{\cdot}s^{-2}$) compared to distance swimming (SG- 2.21 $m{\cdot}s^{-2}$; DG- 1.85 $m{\cdot}s^{-2}$). It is therefore suggested, in addition to other factors, that the greater end back elbow angle when sprinting, contributes to the greater propulsion generated in terms of a higher net force$_{COM}$ and acc$_{COM}$ during the push phase compared to distance swimming.

No quantitative data are provided in the literature with respect to the elbow angle when entering the water. Moreover, to date, this variable has not been investigated over a range of swim velocities. This study revealed that the difference between paces in magnitude of elbow angle at entry approached significance, with both groups displaying less elbow flexion at sprint than distance pace. It is suggested that all swimmers may have maximised the elbow angle prior to entry to avoid extending the arm within the water environment when sprinting, and in doing so increasing resistive drag. This can be explained due to the fact that water is 100 times denser than air; therefore any movement in the water creates more drag. The disadvantage of this characteristic is that an extended arm on entry when sprinting would increase wave drag due to a larger cross sectional area entering the water momentarily. At distance pace, all swimmers reduced the elbow angle at entry. Researchers have recommended this technique, so that the hand creates a ‘hole’ for the wrist and elbow joints to subsequently travel through, thus minimising wave drag. However, extending the upper limb in the water thereafter would increase form drag. It is therefore clear that all swimmers adjust the magnitude of the elbow angle as the hand enters the water, depending on the swim velocity, perhaps due to the resistive characteristics of the hand entry technique.

All swimmers changed the duration (%SC) of the stroke phases between paces. This is in agreement with the literature which indicates that swimmers adapt the time spent in stroke phases to meet the physiological and performance objectives of the event distance (Chollet et al., 2000; Millet et al., 2002; Lerda and Cardelli, 2003; Seifert et al., 2004a; Seifert et al., 2004b; Seifert et al., 2007a; Seifert et al., 2007b). Relative to distance swimming, sprinting is characterised by a shorter entry phase and a longer pull, push and recovery phase, permitting more time within the propulsive phases (pull and push) and less time in the non-propulsive phases (entry), resulting in a longer application of propulsive forces (Millet et al., 2002; Lerda and Cardelli, 2003; Seifert et al., 2007a). All swimmers spent longer in the recovery phase when sprinting relative to distance swimming, as a way to compensate for the shortening of the entry phase, thus allowing an earlier start of the pull phase and a relatively longer muscular recovery time (Chollet et al., 2000; Seifert et al 2004b). Maximum COM deceleration was also found to occur during the recovery phase irrespective of the swim pace. Relative to sprinting, distance swimming is characterised by a longer entry phase and reduced pull, push and recovery phases. These findings support previous studies that have identified that swimmers adopt this style to improve the hydrodynamic position of the body during the distance event (Chollet et al., 2000; Lerda and Cardelli, 2003; Seifert et al., 2004).

The magnitude of elbow angle range during the pull phase (46.81°-SG and 53.77°-DG) is not in agreement with some of the statements in the literature advocating that a 90° angle should be held constant throughout the propulsive (pull), or that it changes minimally throughout the SC (Counsilman, 1973; Costill et al., 1992; Voronstov and Rumyantsev, 2000; Maglischo, 2003). However, the findings of this study are in agreement with those of Payton et al. (1999) who reported the elbow angle range during the pull phase as 45°. Therefore, the fact that swimmers are identified to progressively change the magnitude of the elbow angle during the pull phase, challenges the assumptions implied in the literature in relation to a constant 90° angle throughout the underwater SC, and will consequently have implications in terms of how swimmers are taught/coached.

Another interesting finding with respect to the temporal changes within the SC was the occurrence of the catch position (1st back elbow angle position), which was also significantly different ($p < 0.05$) between paces for both groups. Figure 5.10 indicates that both groups made the catch at approximately 30% and 40% of the SC for sprint and distance swimming respectively.

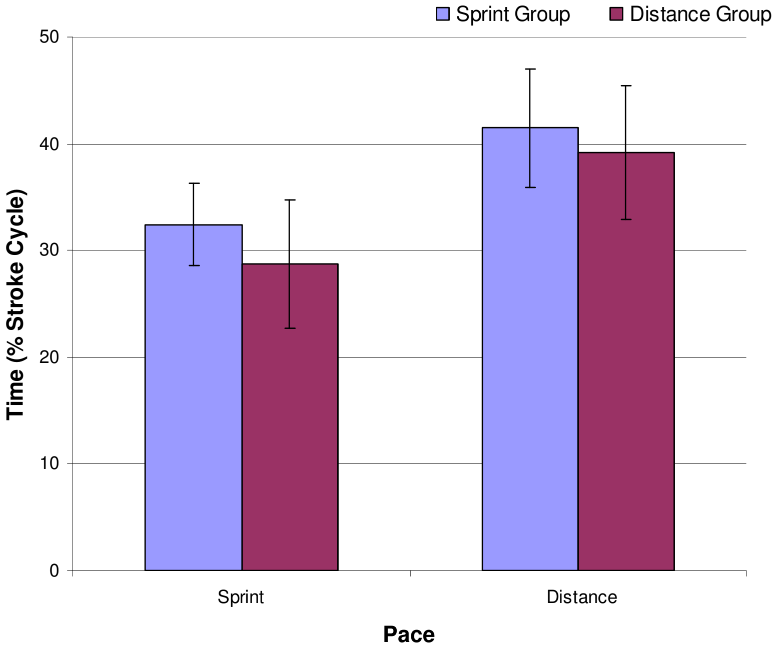


Figure 5.10: Time (% SC) corresponding to the catch for both swim groups, swimming at sprint and distance pace.

It is suggested that the later occurrence of the catch position is also due to the 10% greater duration of the entry phase, when distance swimming. Research studies have recommended that sprint swimmers make the catch earlier in the SC to enable a longer period of propulsive force as a proportion of the SC than distance swimmers (Colwin, 1969; Duclos et al., 2002; Lerda and Cardelli, 2003; Seifert et al., 2004). Similarly, it has been proposed that distance swimmers intuitively increase the time between entry and catch, thereby increasing the duration of the entry phase, to adopt a posture that reduces the hydrodynamic resistance (Keskinen and Komi, 1993; Chollet et al., 2000; Seifert et al., 2004a). The results obtained from this study are not strictly in agreement with the above. SG and DG do not obtain the catch at significantly different times in the SC. All swimmers make the catch earlier when sprinting, and later when swimming at distance pace. As suggested in the literature, it is reasonable to assume that swimmers obtain the catch earlier when sprinting to apply propulsive forces for a greater proportion of the SC and later at distance pace to enhance the hydrodynamic position of the body. Although Maglischo (2003) and Costill et al. (1992) recommended that the catch be attained at 30% of the SC, they did not differentiate between swimming paces. This study indicates that the time to catch is dependent on whether the swimmer is sprinting or distance swimming and not related to the distance specialisation of the swimmer as suggested in the literature.

This study revealed that all swimmers increased the total shoulder roll when distance swimming relative to sprinting. Researchers have proposed that this action reduces the frontal surface area and consequently minimises active drag (Cappaert et al., 1995; Cappaert, 1998; Castro et al., 2002). Moreover, Cappaert et al. (1995) proposed that reducing the difference between shoulder and hip roll magnitude would be beneficial in terms of minimising active drag. In this study, the difference between total shoulder and hip roll was less at distance pace for SG (53.87°) and DG (59.55°) than in sprinting (70°- SG; 66°- DG), confirming that all swimmers adopted a more streamlined or improved hydrodynamic body position when swimming at a distance pace.

Moreover it was found that the total shoulder roll changed between swim velocities due to the contribution of the right shoulder roll adjusting between paces and not the left shoulder. This finding may be due to an asymmetric stroke pattern, which is discussed subsequently. Nonetheless, researchers have proposed that an increase in shoulder roll with increasing race distance is due to a longer entry phase (Cappaert, 1998; Castro et al., 2002). It is therefore possible that the increased shoulder roll may be due to the longer entry phase per se, or due to the increase in overall time allowing for more roll. Further, an increase in duration of the entry phase, longer SL and reduced SF has been related to better economy in distance swimming than sprinting. In this study, the SL increased by 0.24 m (SG) and 0.23 m (DG) respectively, concomitant with a decrease in SF of 16.05 cycles/min (SG) and 14.12 cycles/min (DG), when swimming at distance pace. These results suggest that a greater shoulder roll at distance pace can facilitate a more economical stroke due to the associated effects of other variables i.e. increased duration of entry phase, SL and reduced SF. In sprint swimming economy is not the main consideration for the swimmer. The objective is to maximise propulsive forces throughout the SC (Costill et al., 1992; Cappaert, 1998; Chollet et al., 2000; Seifert et al., 2004a). Thus, the high SF does not enable as great a body roll to be achieved due to the reduced time available to roll.

The influence of body or shoulder roll has been addressed frequently in the literature. However, the hip roll as a separate entity has not. This may be due to the methods implemented in previous studies (e.g. the balsa fin or PVC stick method) that accounted only for total trunk rotation. This study indicated that the magnitude of the maximum hip roll to both sides was significantly greater at distance than at sprint pace. The magnitudes of the hip roll in this study were similar to those obtained by Cappaert et al. (1995), for sprint swimming, and Psycharakis (2006), for distance swimming. The large difference in magnitude of hip and shoulder roll further supports the independency of the hips and shoulders in that a change in one is not necessarily reflected in a proportional change in the other. Indeed, hip roll was 8° greater at distance than sprint pace, whereas the shoulder roll was only 4° greater. Moreover the significant interaction between pace and shoulder/hip revealed that both groups changed the time to maximum hip roll more than the shoulders. This finding further supports the assumption that the hip is independent of the shoulders, and is more subject to change between paces than the shoulders. This issue of independence of the hips and shoulders has never been addressed previously in the literature.

It was also proposed that the magnitude of the kicking action may contribute to the change of hip rotation between paces for both groups, due to the generated torques about the longitudinal axis. It was suggested that the hip rotation is dampened when sprinting due to the vigorous action of the leg-kick as indicated by Yanai (2001). The decreased foot vertical displacement magnitude when kicking at distance pace may not produce torques as powerful as that in sprint swimming, permitting the swimmers to increase hip rotation during this pace. It is therefore concluded that the magnitude of the kicking action may determine the degree of hip and consequently shoulder roll between swim paces.

This raises the issue of the timing of attaining maximum shoulder and hip roll. The time corresponding to maximum hip roll (both sides) revealed that all swimmers reached maximum left and right hip roll later in the SC when swimming at distance than sprint pace (Figures 5.11 and 5.12). The longer time to reach maximum rotation of the hips at distance pace may be related to the reduced vertical kicking displacement of the feet at this pace. It is assumed that the kick is not as aggressive when distance swimming and therefore the torques produced from the leg-kick are diminished in comparison to sprinting, resulting in a longer period to obtain maximum hip rotation at distance pace.

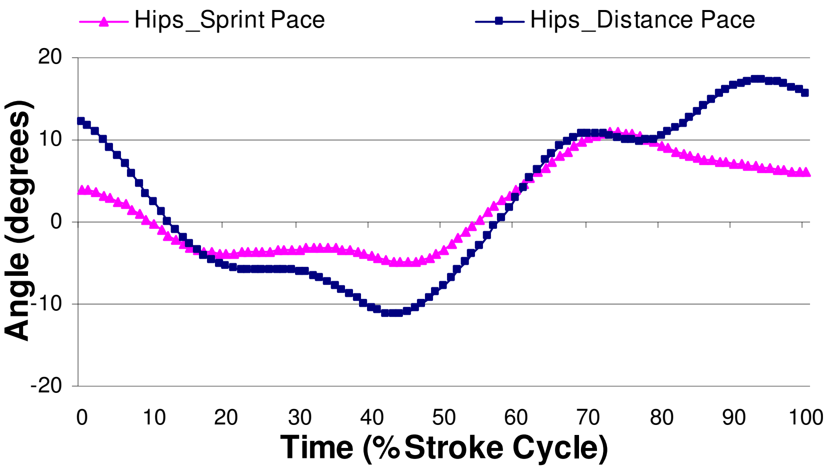


Figure 5.11: Time (%SC) to maximum left (negative) and right (positive) hip roll for the SG.

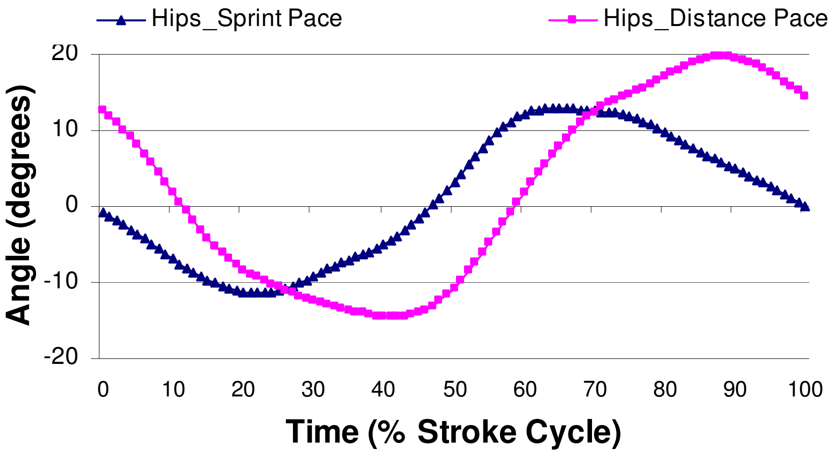


Figure 5.12: Time (%SC) to maximum left (negative) and right (positive) hip roll for the DG.

Similarly, the time to maximum right shoulder roll also occurred significantly later at distance than sprint pace for both groups, whereas the maximum left shoulder remained unchanged between paces. Table 5.2 illustrates the position, in terms of stroke phase, of each hand at maximum right shoulder roll. Maximum right shoulder roll occurred on the borderline of hand exit when sprinting- whereby shoulder roll has been linked to permitting longer application of propulsive forces (Colwin, 1969; Leonard, 1992; Maglischo, 2003), or during the recovery phase when distance swimming, whereby shoulder roll has been linked to assisting arm clearance over the water (Colwin, 1969; Leonard, 1992; Maglischo, 2003). The later attainment of maximum right shoulder roll when distance swimming relative to sprinting is also most likely due to the contribution of the leg kick as identified previously.

	Right Hand	*Left Hand*
SG: Sprint Pace	Recovery Phase	Initiating Pull
DG: Sprint Pace	Prior to hand exit	Entry
SG: Distance Pace	Post hand exit, in recovery	Entry
DG: Distance Pace	Post hand exit, in recovery	Pull

Table 5.2: Hand positions, in stroke phases, at maximum right shoulder roll.

By assessing the time to maximum shoulder and hip roll relative to one another, it is possible to obtain an indication of a potential relationship between these two variables, which has not been established in the literature. In section 5.1 it was outlined how each group changes the temporal relationship between the shoulders and hips between paces. It was proposed that the kicking action may have controlled the different sequencing of the shoulders and hips between groups. Similarly it is proposed that the different sequencing between paces is a consequence of the leg kicking action. When sprinting, all swimmers displayed a greater vertical displacement of the feet which may have produced greater torques originating at the feet travelling along the body towards the shoulders. This may be beneficial in terms of transmitting energy from the hips to the shoulders, allowing the arms to subsequently direct energy back through the stroke pattern. Similarly, because the DG were found to lead with the shoulders followed by the hips at distance pace it is speculated that these swimmers utilise this technique as a method of directing water flow along the body progressively from shoulders to feet. Moreover, the fact that the vertical displacement of the feet was less at distance pace than sprint pace for all swimmers suggests a reduced torque effect from the legs, which may have been responsible for shoulders leading followed by the hips. Further exploration of the flow of motion/energy along the body in swimming is necessary to assess the rotational movement about the shoulders and hips and their sequencing between swim paces. Although a possible energy effect may be responsible for the different hip and shoulder roll patterns when sprinting and swimming at a distance pace (due to the torques generated by the kicking action), it is presently speculation. However, based on the work by Sanders and Psycharakis (2008), who demonstrated that a body wave was transmitted from the hips to the ankles during freestyle swimming, it is also possible that energy is transferred along the body and perhaps changes in direction depending on the swim velocity. Thus further investigation is required.

Quantitative data with regard to the foot ROM when kicking has not been presented in the literature to date, and thus comparisons with previous research is not possible. The magnitude of the kicking action has been linked to the change of many variables between paces as presented previously. However, the primary purpose of a greater foot vertical displacement when sprinting is to increase propulsion (Wilke, 1992; Deschodt et al., 1999; Maglischo, 2003). The decreased vertical range during prolonged periods of distance swimming may not produce as much propulsive force as when sprint swimming, but may be advantageous in terms of reducing the frontal surface area and minimising active drag. Between the paces, the SG appeared to reduce the foot vertical displacement range the most at distance pace and it is proposed that they were unable to sustain, perhaps due to physiological capacity, a magnitude similar to that of the DG throughout the distance event.

It should also be highlighted that the foot vertical displacement range did not differ across groups. That is, all swimmers display a similar kicking range at each swim pace. This finding is contrary to that of Cappaert (1998) who reported that one of the most distinguishable differences between sprint and distance swimmers was the knee range of motion, which in turn creates a greater foot displacement range. It was suggested that an increase in knee ROM would increase propulsion. This study indicates that there are no differences between SG and DG in terms of the magnitude of foot vertical displacement range, but that all swimmers change this variable depending on swim pace.

5.2.1. Summary of Changes between Paces

The stroke kinetics, race parameters and durations within the stroke phases all changed between sprint and distance pace in order to meet the physiological requirements of the race distance. The magnitude of the elbow angle within the end back event and the range within the push phase differed between paces which contributed to the adjustment of the kinetic variables. Due to the relative timing between the arms, the entry and push phases were the most propulsive irrespective of swim pace, whereas the most decelerative phase occurred during the recovery. The prolonged duration of the entry phase, when distance swimming, resulted in a delayed attainment of the catch position and maximum stroke depth at distance pace compared to sprint pace. Shoulder and hip roll appeared to influence the magnitude of average vertical and lateral range displacement of the finger between paces. In turn, the magnitude of the kicking action appeared to influence the sequencing of the shoulders and hips, in terms of both magnitude and timing, due to the different torques generated by the legs over the swim paces. Moreover the kicking action was also related to the forward extension of the right arm after entry.

The findings of this study indicate that all swimmers adapt their swimming technique in relation to the above variables depending on the swim velocity. It is proposed that swimmers make this adjustment, whether it is intuitive or learned in order to maximise their performance at that particular race distance. Moreover, the literature provides recommendations with regard to the different stroking characteristics between sprint and distance swimmers. This study revealed, in relation to most variables, that this is not necessarily the case. SG and DG swimmers are not overwhelmingly different in terms of their technical characteristics, but all swimmers adjust certain variables depending on the swim pace in order to meet the race distance outcomes.

5.3. Commonalities between Groups and Paces and Individual-Specific Adjustments.

This section discusses the variables that were not subject to change between groups or paces. Another dimension to this section is to highlight any individuals who changed their technique between paces as a way to optimise their individual performance.

Neither group changed their stroke kinematics between paces with respect to the maximum stroke depth and stroke width (measured by the vertical and lateral displacements of the finger, wrist and elbow segments). The maximum stroke width in this study (0.39 m), was in general agreement with Schleihauf et al. (1988): 0.37 m; Payton and Lauder, (1995): 0.34 m; and Payton et al. (1999): 0.27 m. Similarly, maximum stroke depth (0.66 m) was comparable to that reported by Costill et al. (1992): 0.4-0.6 m; Payton et al. (1999): 0.79 m; and Maglischo, (2003): 0.5-0.7 m. Cappaert's (1998) study was the main exception to this trend, in which the main difference between sprint and distance swimmers was the stroke depth with values of 1.6 m and 1.0 m respectively. These values far exceed those in both the current literature and the data obtained from this study. It is suggested that perhaps this was a misprint or problem with the methodology implemented.

Nevertheless, the fact that no change occurred across paces is contrary to that reported in the literature which associates sprint swimming with a greater stroke depth than distance swimming (Colwin, 1977; Cappaert, 1998; Voronstov and Rumyantsev, 2000). This assumption is based on the fact that a deeper stroke depth allows a larger cross-sectional area of the upper limbs to apply force. Moreover, Voronstov and Rumyantsev (2000) demonstrated that an extended elbow requires a greater muscular torque about the shoulder than a flexed elbow, which is characterised by a reduced length of the levers and inertia of the arm. Therefore, it was assumed that a 'straighter arm' pull may be unsustainable, in terms of muscular effort over longer distances, which would result in swimmers adopting a reduced elbow angle and consequently a smaller stroke depth. The literature does not provide sufficient quantitative data with regard to the maximum lateral displacement of the upper limbs, but there has been speculation that due to a greater body roll during distance swimming, lateral displacement of the upper limbs also increases at this pace. These assumptions were not evident in this study in terms of the group as a whole.

On an individual basis, some swimmers changed the magnitude of both maximum vertical and lateral displacement of the finger across paces. With regard to maximum vertical displacement, sprint participants 2 and 3 increased and decreased the stroke depth by 0.10 m and 0.13 m respectively at distance relative to sprint pace. Similar adjustments were evident with respect to the wrist and elbow joints. Due to the association between stroke depth and the magnitude of the elbow angle (Cappaert, 1998), this parameter was investigated in relation to the above participants. Figure 5.13 indicates that sprint participant 2 increased the elbow angle at distance pace whilst sprint participant 3 increased the elbow angle when sprinting. These findings support the suggestion that the stroke depth is influenced by the magnitude of elbow angle. However, with only two participants indicating this association, more research is warranted.

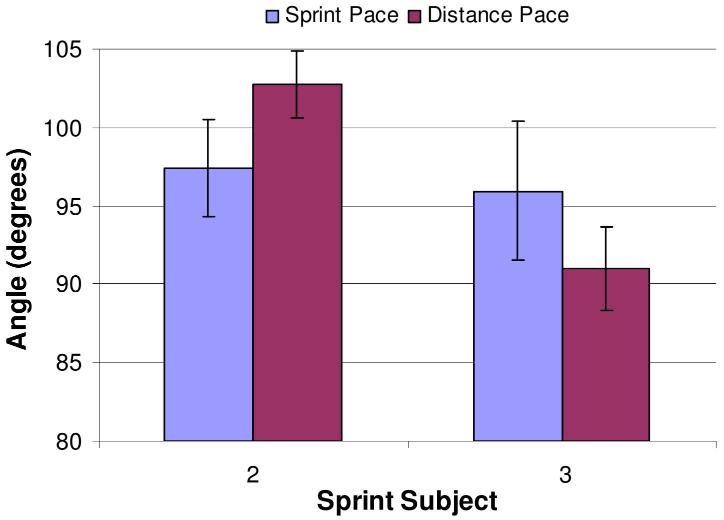


Figure 5.13: 'Shoulder x' elbow angle between sprint and distance pace for sprint participant 2 and 3.

With regard to the maximum lateral displacement, distance participants 2, 3, 6 and 8 all increased the maximum lateral displacement of the finger when sprinting, compared to distance swimming, whereas distance participant 7 reduced this variable at sprint pace. Because body roll has been thought to influence the medio-lateral aspect of the stroke pattern (Lui et al., 1993; Hay et al., 1993; Payton and Mullineaux, 1996), this was investigated. However, no association was apparent in relation to these individuals. It therefore appears that the adjustment of maximum lateral displacement of the finger between paces for these participants is influenced by an additional factor and is independent of body roll. This may be due, for example, to the swimmers' attempts to optimise the vortex shedding characteristics of the hand path. The literature proposes that swimmers can shed vortices prematurely in the stroke pattern due to a sudden directional change combined with excessive acceleration and application of force (Colwin, 2002). Thus, it is possible that the adjustment is due to the swimmers attempts to avoid premature shedding of the vortices.

The above results indicate that some swimmers adjust their swimming technique between paces in relation to changing the maximum vertical and lateral aspect of the stroke pattern. Because no consistent trend of directional change between paces was observed, it appears that the above individuals change their technique between paces to optimise their own individual swim performance.

The importance of the elbow angle during the underwater phase of the SC has been emphasised in the literature. Figures 5.14 and 5.15 present the average elbow angle profiles with respect to the first arm entering the water, for both groups at sprint and distance pace respectively. Each profile is divided into stroke phases to identify the activity of this variable within each phase. Following hand entry at both paces, all swimmers extended the elbow. After the entry phase, the elbow angle decreased during the pull phase until the hand was vertically aligned with the shoulder (representing the end of the pull phase). Thereafter the elbow angle extended during the push phase until hand exit. The recovery phase contained both a sharp decrease and increase in elbow angle representing the time the elbow travels from behind the shoulder axis to the arm beginning its forward extension for re-entry.

Interestingly the average elbow angle did not approach 90° at any time during the underwater phases of the SC. This is not in agreement with the recommendations that swimmers should stroke with a 90° angle throughout the underwater phases of the SC (Colwin, 1969; Colwin, 1977; Maglischo et al., 1989; Costill et al., 1992; Maglischo, 2003). Moreover, many researchers have advocated that the elbow angle should not change, or change minimally throughout the pull and push phases. It is evident from Figures 5.14 and 5.15 that the elbow angle changes continuously during the underwater phase.

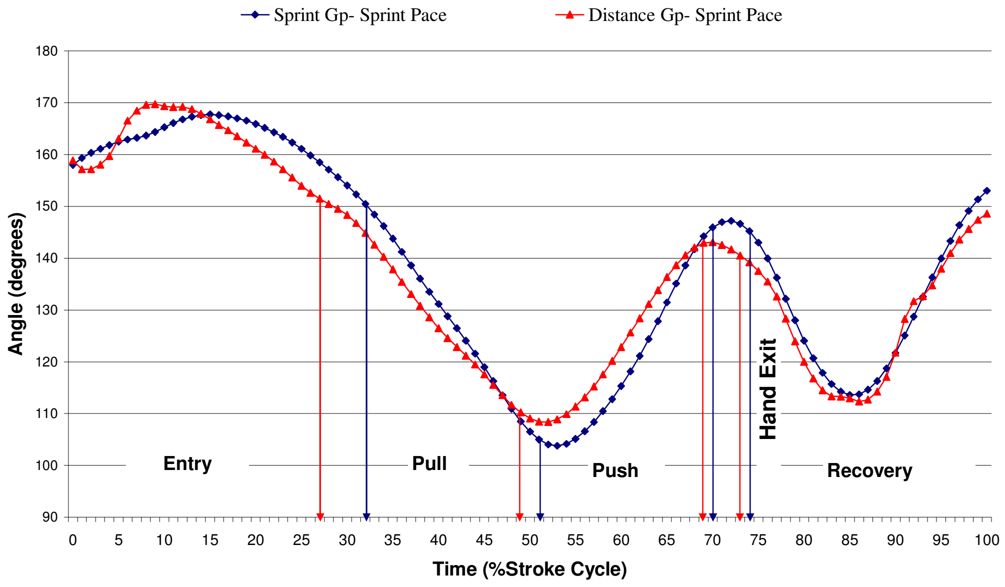


Figure 5.14: Average elbow angle data for SG and DG, swimming at sprint pace. The stroke phases are identified throughout the stroke cycle and colour coded to match the swim group.

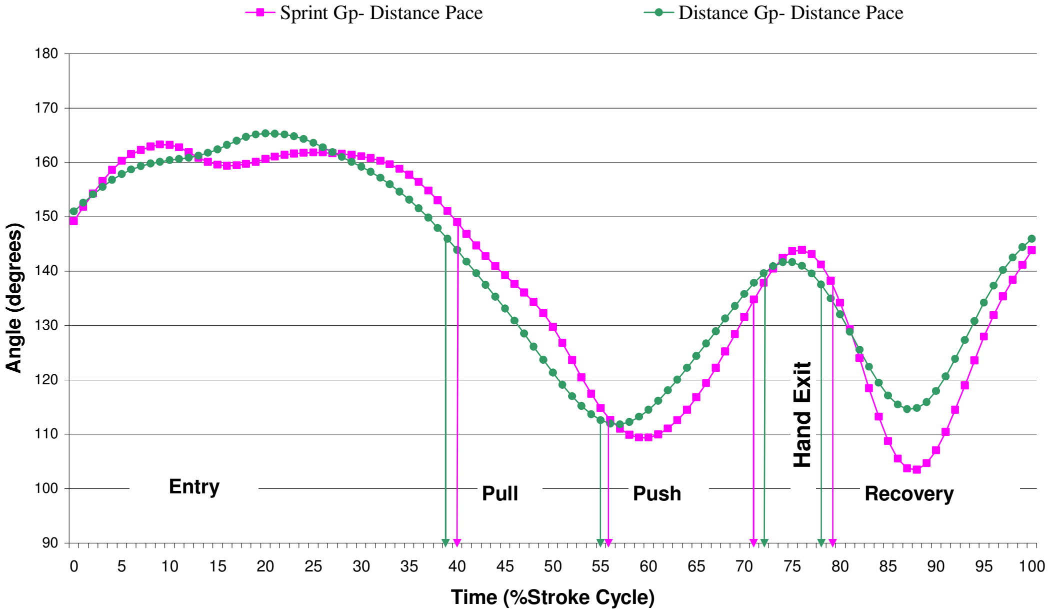


Figure 5.15: Average elbow angle data for SG and DG, swimming at distance pace. The stroke phases are identified throughout the stroke cycle and colour coded to match the swim group.

The minimum elbow angle for both right and left sides was not significantly different between paces. The magnitude of the minimum elbow angle (approx. 95°) in this study are similar to the 90-100° angle recommended in the literature (Colwin, 1969; Counsilman, 1973; Maglischo et al., 1989; Costill et al., 1992; Maglischo, 2003), but do not support the view that at greater velocities, swimmers increase the elbow angle to permit greater application of forces (Voronstov and Rumyantsev, 2000). That is, all swimmers, independent of group or pace, utilise a similar minimum elbow angle.

Nevertheless, some individuals did change the minimum elbow angle across paces (Figure 5.16). Sprint participants 3 and 6, and distance participants 1 and 7 all reduced the minimum elbow angle at distance than sprint pace, whilst distance participants 3 and 8 both increased this variable when distance swimming. Although the majority of swimmers who changed the magnitude of this variable between paces showed a tendency to increase the minimum elbow angle when sprinting, this trend was not conclusive. Because there was no decrement in swim performance by these individuals, it appears that these swimmers change the magnitude of the minimum elbow angle in an individualised manner so to optimise their own performance.

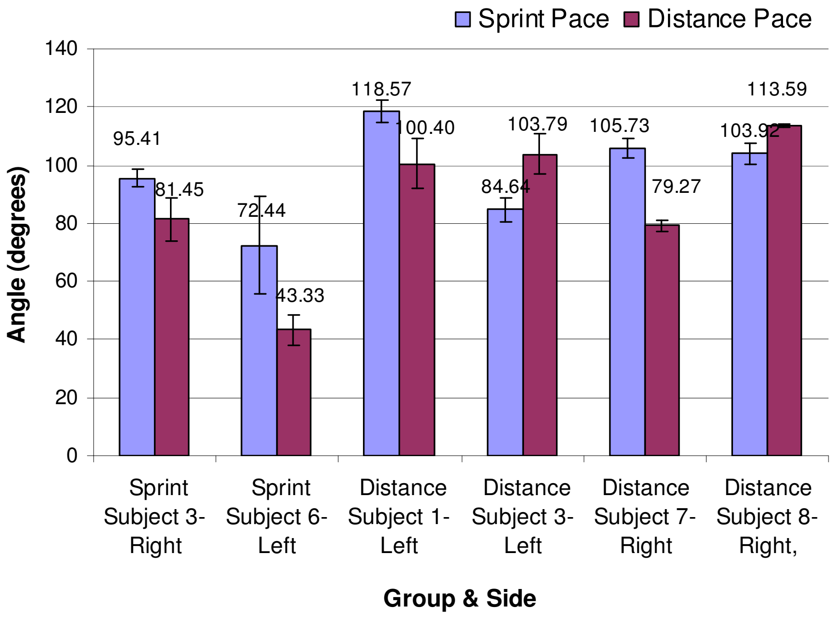


Figure 5.16: Individuals who change the magnitude of minimum elbow angle between sprint and distance paces.

Nonetheless, based on the literature, it may be speculated that the advantage for some swimmers to utilise a larger elbow angle when sprinting may be associated with a greater application of propulsive force (due to the increased cross-sectional area of the arm in this position). A larger elbow angle has also been associated with a greater motor recruitment about the shoulder muscles which may induce local muscular fatigue during longer races. It is possible that swimmers reduce the elbow angle at distance pace to apply a smaller propulsive force requiring less motor recruitment. Distance participants 3 and 8 did not display the above trend. Alternatively they employed larger elbow angles when swimming at a distance pace, perhaps as a way to maximise their performance.

Moreover, it was also observed that all the above participants who indicated a change of minimum elbow angle across paces, also appeared to change the magnitude of finger lateral displacement range between paces (Figure 5.17). To be precise, those who had a larger minimum elbow angle whilst swimming showed a decreased finger lateral displacement range at that particular pace, and vice versa. Perhaps a greater elbow angle inhibited the lateral range of motion of the upper limb and vice versa. To establish a more definitive relationship between these two variables requires further analysis, however it is obvious that these variables are logically connected. It appears that some individuals change the magnitude of minimum elbow angle and the lateral displacement range of the upper limb between paces without adversely affecting their swim performance. These swimmers appear to change their technique as a way to optimise their own performance at that particular pace. The fact that there was no consistent change of the swimmers' technique across paces, further supports the individual aspect of these adjustments between paces.

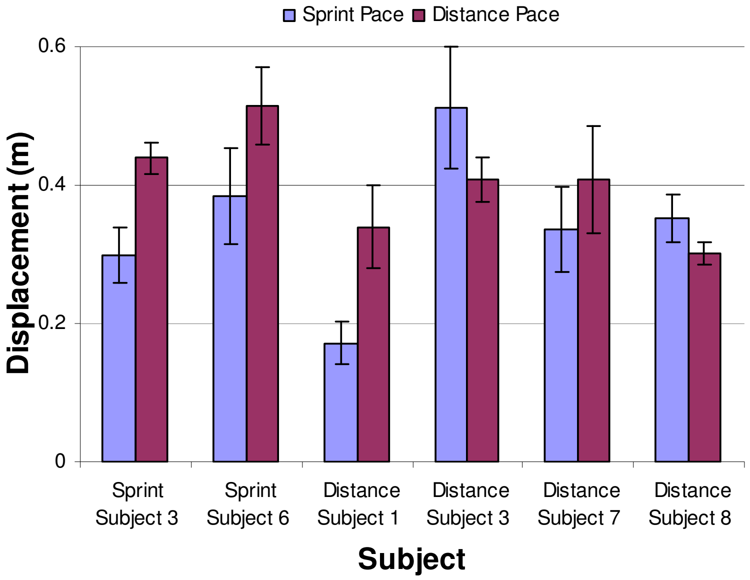


Figure 5.17: Swimmers who had a greater minimum elbow angle across paces also had a different range of lateral displacement of the finger between paces.

Although the 'catch' event is regarded as fundamental to swim propulsion, no quantitative data are reported in the literature with regard to its magnitude (Costill et al 1992; Maglischo, 2003) or whether it varies in relation to swim group or swim pace. The results from this study indicated that the angle of the elbow at catch does not change between paces regardless of swim group and is in the range of 150.99°-155.15°.

Researchers have advised that a large hand exit elbow angle causes the swimmer to displace water upwards and thus consequently drive themselves down in the water as a reaction (Costill et al., 1992). Similarly a reduced elbow angle at this position may reduce the magnitude and duration of the force. It is therefore essential that this angle is optimised, yet no recommendations are provided in the literature with regard to the magnitude of this variable, or whether it varies according to the swim pace. This study revealed that both groups do not change the magnitude of elbow angle at hand exit across paces. However, some individuals adjusted the magnitude of this variable across paces, with the majority of participants decreasing this angle at distance pace compared to sprint swimming (Figures 5.18 and 5.19). It is suggested that those swimmers who reduced the elbow angle as the hand exits the water enable an efficient exit of the hand at the end of the underwater SC.

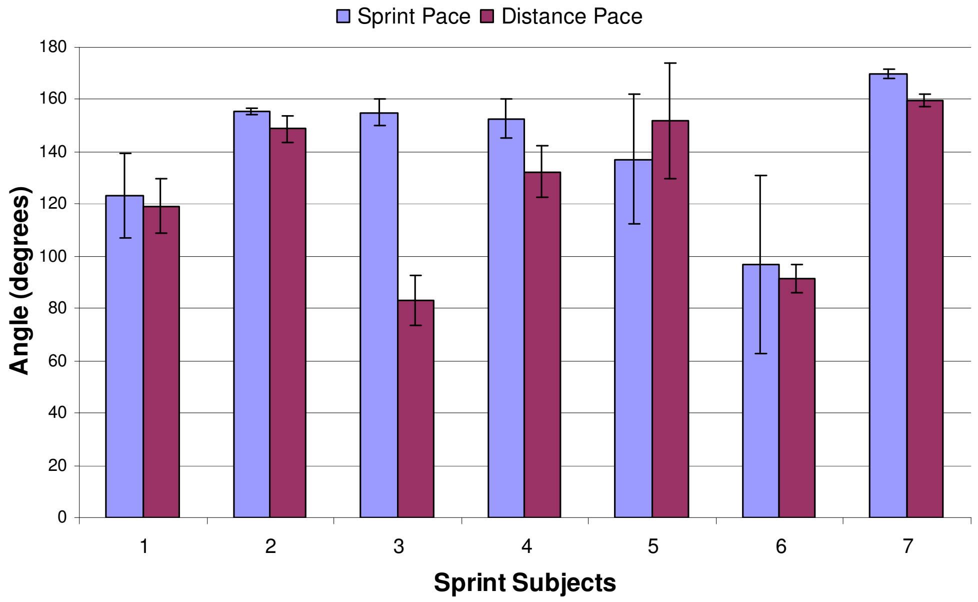


Figure 5.18: Elbow angle at hand exit between sprint and distance- SG

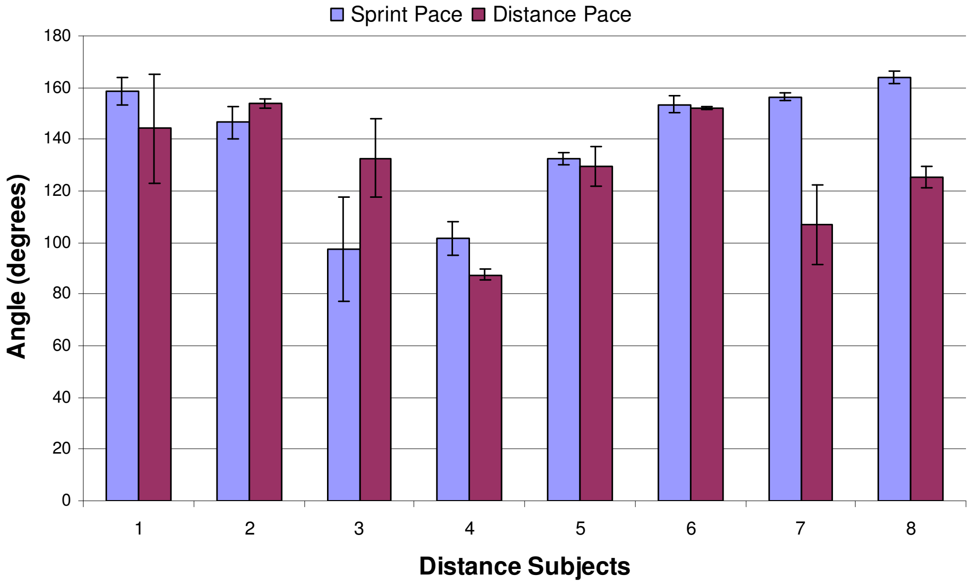


Figure 5.19: Elbow angle at hand exit between sprint and distance- DG

Another main finding across trials was the asymmetry of the shoulder and hip roll. That is, for both variables, participants typically roll more to one side than the other. Similar to the findings by Psycharakis (2006) it was revealed that all swimmers rolled the shoulders more to the left side than to the right. Both groups rolled the hips significantly more to the right side. This further indicates the ability of the hips to rotate independently of the shoulders. It may be speculated that the asymmetry is related to maintaining the body in alignment. Asymmetry of the shoulders has been identified with respect to breathing, with a greater shoulder roll to the breathing side (Payton et al., 1999; Castro et al., 2002). However, all trials in this study were performed under non-breathing conditions. Symmetry of arm coordination in freestyle swimming has also been associated with motor laterality (arm dominance) and the preferred side of breathing (Seifert et al., 2005). Seifert et al. established that swimmers who breathe unilaterally are predisposed to an asymmetric stroke action. Even though the swimmers did not breathe during the trials it is possible that, through training, they have developed an asymmetric stroke pattern which incorporates the rolling action of the shoulders and hips. Moreover, arm dominance has been associated with greater hand velocities and propulsive forces (Rushall et al., 1994; Keskinen and Keskinen, 1997; Maglischo, 2003). This may have resulted in an asymmetric pulling pattern thereby affecting the magnitude of shoulder roll. Further, Seifert et al. (2005) found that most freestyle swimmers illustrate asymmetric arm coordination with propulsive discontinuity on the side of the non-dominant arm and propulsive superposition on the side of the dominant arm.

It has been proposed (Maglischo et al., 1988; Maglischo, 2003) that front crawl swimmers fall into one of the following categories: a one-peak or two-peak velocity COM profile (per arm stroke). It was unknown whether a group would favour one style than the other, or whether the swim velocity may determine the velocity profile. The majority of swimmers had a two-peak COM velocity profile, independent of swim velocity. Sub-dividing the COM velocity profile into the various stroke phases, it is evident that the majority of swimmers display two peaks corresponding to the 1) push phase and 2) hand exit (Figure 5.20). As suggested by Maglischo (2003), no peak occurred during the pull phase. It should also be highlighted that these illustrations do not take into consideration the effect of the leg kick during the SC, consequently these interpretations should be considered cautiously.

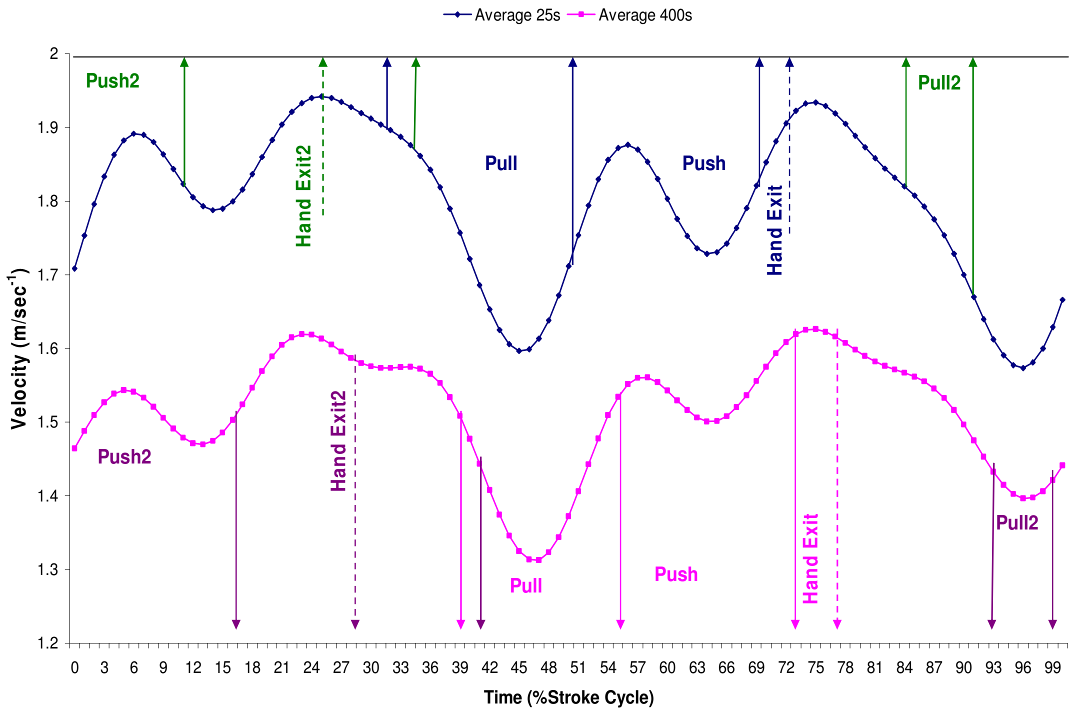


Figure 5.20: Two peak velocity profile of sprint swimmer 3 when sprinting and distance swimming. The two velocity-normalised time profiles are the mean of the three trials for each event distance. Blue and pink lines represent the stroke phases of the first arm entering the water at sprint and distance pace respectively- time = 0%- hand entry, time= 100%- hand re-entry. Green and purple lines indicate the stroke phases of the second arm entering the water at sprint and distance pace respectively.

In this study, no participant displayed a one peak COM velocity profile when sprinting. Figures 5.21 and 5.22 illustrate two participants who utilised a one peak velocity profile when distance swimming. Both swimmers had a prolonged peak that occurs as a combination of the pull and push phases and hand exit, which is in general agreement with Maglischo (2003). One period of deceleration, or domination of resistive forces, is obvious throughout the SC which corresponds with the pull phase.

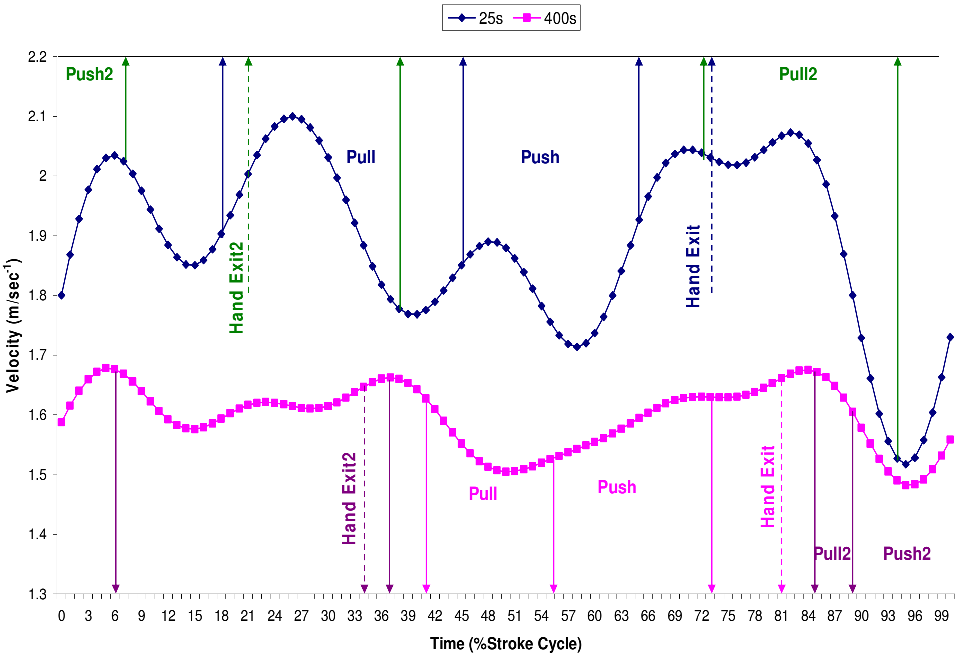


Figure 5.21: One peak velocity profile during the distance pace. A two peak velocity profile is evident at sprint pace. The two velocity-normalised time profiles are the mean of the three trials for each event distance. Blue and pink lines represent the stroke phases of the first arm entering the water at sprint and distance pace respectively- time = 0%- hand entry, time= 100%- hand re-entry. Green and purple lines indicate the stroke phases of the second arm entering the water at sprint and distance pace respectively.

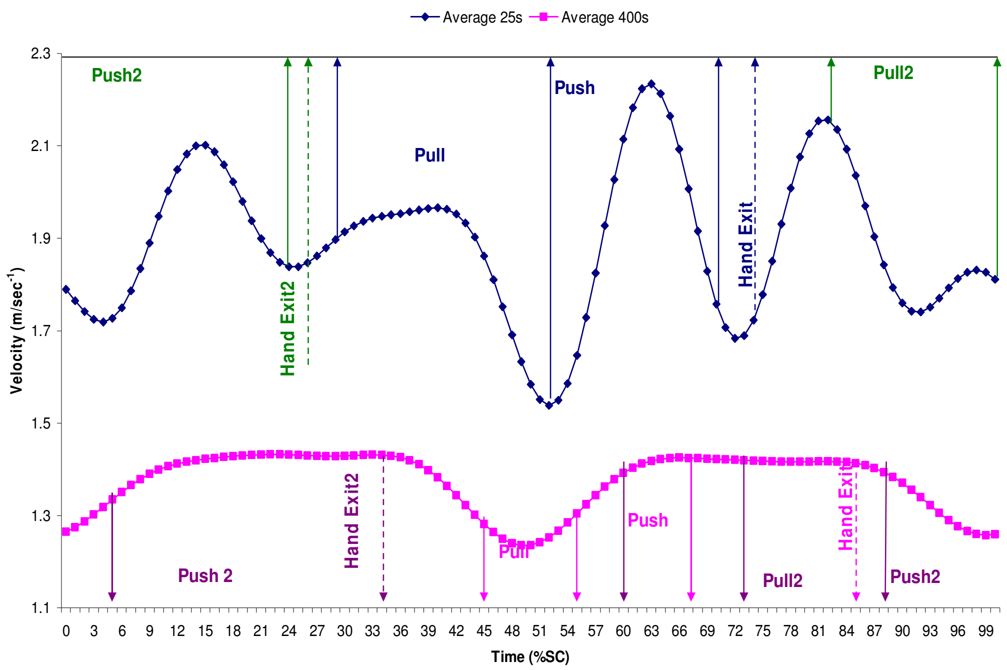


Figure 5.22: One peak velocity profile during the distance pace. A two peak velocity profile is evident at sprint pace. The two velocity-normalised time profiles are the mean of the three trials for each event distance. Blue and pink lines represent the stroke phases of the first arm entering the water at sprint and distance pace respectively- time = 0%- hand entry, time= 100%- hand re-entry. Green and purple lines indicate the stroke phases of the second arm entering the water at sprint and distance pace respectively.

Maglischo (2003) proposed that swimmers with a one peak velocity pattern tend to utilise a less diagonal (lateral) stroke pattern and a minimal kicking rhythm than those who have a two peak velocity pattern. Sprint participants 3 and 6, and distance participants 1 and 4, all displayed a one peak velocity profile at distance pace. These participants were examined with regard to lateral displacement of the finger during the underwater stroke phase. It was observed in the results chapter that sprint participants 3 and 6, and distance participants 1 and 4, all increased the lateral displacement range at distance compared to sprint pace. All other participants, who displayed a two peak velocity pattern at distance pace, did not show such distinct changes with respect to finger lateral displacement range. Consequently it is suggested that one-peak velocity swimmers may be characterised by a greater lateral displacement of the finger, with no change in magnitude of shoulder or hip roll between paces. This finding is contrary to Maglischo (2003). Perhaps the greater lateral displacement of the finger when distance swimming inhibits the directional change of upper limb throughout the SC resulting in a reduced capability of generating two-peaks per armstroke when distance swimming.

The two peak velocity pattern was recommended by Maglischo (2003) due to the greater potential to be effective in terms of achieving a higher velocity per SC. Post analysis, the total sum of each swimmer's average V_{COMhor} profile, over one SC (based on the mean of three trials), was analysed to investigate a possible connection with this variable and the peak velocity style pattern. The sum velocity was used as an indication of total COM velocity profile, including both the propulsive and resistive activities throughout the SC. Figure 5.23 reveals that whether a swimmer is typified by a one or two peak velocity pattern does not appear to have any associated advantage with respect to obtaining a greater velocity per SC.

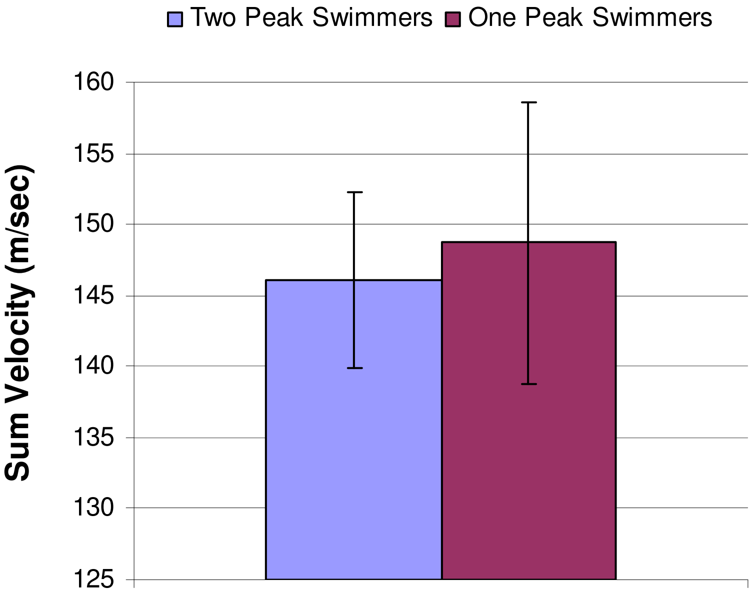


Figure 5.23: Sum velocity throughout the SC for one (4 participants) and two peak velocity profilers (10 participants).

It is therefore concluded that the majority of swimmers utilise a two peak velocity pattern when swimming at both paces. Some participants displayed a one peak velocity pattern, but this occurred only at distance pace. No apparent benefits were associated with the use of a one or two peak velocity pattern. A possible relationship may exist between the one peak velocity pattern and lateral displacement of the finger during the SC; based on the fact that all these participants increased the lateral motions of the finger when distance swimming, but more research is required. Moreover the style of velocity profile, i.e. whether one or two peak, does not appear to be typically associated with either the race distance specialisation of the swimmer, or the swim velocity.

5.3.1. Summary of the Commonalties and Individual Changes between Paces

This study revealed that the overall group did not always adapt the magnitude of a variable between paces. Alternatively some individuals within each group did respond to the change in pace by uniquely adjusting the characteristics of that particular variable in order to maximise their swim performance. In most cases, the changes amongst the individuals did not have a consistent trend which further supports the notion of individual modifications of swimming technique between paces in order to optimise each swimmers own performance. The variables that displayed individual changes in this study were the maximum stroke depth and width, which were also speculated to relate to the change in magnitude of the elbow angle during the pull phase and the vortex shedding characteristics of the underwater SC respectively between swim paces. Participants also appeared to adjust the magnitude of the minimum and hand exit elbow angle, with the former linked to the lateral displacement of the finger. Finally, only four swimmers displayed a one peak velocity pattern which occurred at distance pace. Contrary to recommendations in the literature, one peak velocity profiles appear to be related to the magnitude of lateral upper limb displacement and no kinetic advantage was observed in relation to either a one or two peak velocity profile.

Chapter Six: Conclusion

The primary purpose of this study was to investigate whether front crawl SG and DG were different in terms of stroke kinematics and linear kinetics.

The second purpose of this study was to investigate whether front crawl swimmers change their stroke kinematics and linear kinetics between sprint and distance pace. This study found that over a broad range of variables, all swimmers adjust their technique between paces in order to optimise performance.

6.1. Groups

Although swimmers specialise in either sprint or distance events, contrary to the literature, this study found that these swimmers are not significantly different in terms of stroke kinematics and linear kinetics. It has been publicised that sprint and distance swimmers differ in terms of the magnitude of stroke depth, stroke width, elbow angle and the foot range of motion. In this study, SG and DG did not differ with respect to the aforementioned variables. Thus, these findings challenge current views with regard to front crawl sprint and distance swimmers.

Cappaert (1998) suggested that sprint and distance swimmers displayed different magnitudes of shoulder roll. In this study, SG and DG did not differ in terms of shoulder or hip roll magnitude. However, it was evident that these swimmers had a different sequencing pattern of the shoulder and hip segments- a characteristic which has not to date been previously investigated. When sprinting, both sprint and distance swimmers rotated the hips prior to shoulders. The SG showed this sequencing pattern distinctively throughout the SC, whereas was less pronounced with respect to the DG. When distance swimming, the DG sequenced the shoulders prior to the hips, whereas the SG rolled the shoulders and hips simultaneously. There was some evidence that the different sequencing order of the shoulders and hips between the groups was related to the magnitude of kicking ROM and a possible energy wave travelling along the body was speculated and requires further investigation.

This study revealed that SG and DG are different with respect to the duration of the pull and push phases. The shorter duration of these phases by the SG was linked to a faster horizontal velocity and vertical acceleration of the hand by the latter group within the pull and push phases. Moreover, the faster average swim velocity and maximum horizontal velocity of the COM by the DG at distance pace, was logically related to the greater hand resultant velocity of the DG relative to the SG.

Maglischo et al. (1989) has shown that front crawl swimmers display either a one-peak or a two-peak COM velocity profile. Maglischo (2003) speculated that the style of velocity pattern differs with respect to the stroke pattern, body roll and kicking rhythm. The COM velocity profile in relation to sprint and distance specialisation has not been examined. In this study, no difference between the groups was found. The majority of swimmers had a two-peak COM velocity profile, whereas two sprint and two distance swimmers had a one-peak velocity profile only at distance pace. Contrary to Maglischo's (2003) assumptions, in this study one-peak COM velocity profile swimmers logically relate to a greater lateral displacement of the finger, however regression analysis is warranted to conclude this finding. In this study, it was also shown that neither style was superior in terms of performance.

In conclusion, the findings of this study challenge current views regarding the differences in kinematics and linear kinetics between sprint and distance front crawl specialists swimming at sprint and distance pace.

6.2. Paces

Despite the distance specialisation, all swimmers changed a broad range of kinematic and kinetic variables between sprint and distance pace.

The magnitude of average vertical and lateral range of the finger's displacement changed between paces, with evidence of a link to the adjustment of shoulder and hip roll magnitude between paces. The end back elbow angle and the range of elbow angle within the push phase were the only elbow angle variables to change between paces (which occur during the end of the underwater stroke phase). It is unlikely that the elbow angle contributed to the altered trajectory of the finger in this study.

The temporal aspects of the stroke trajectory were also noted to change between the paces, primarily due to the varied duration of the entry phase. Specifically, the duration of the entry phase was approximately 10% longer when swimming at distance pace relative to sprinting. Maximum stroke depth and the execution of the catch position were both attained 10% later in the SC when distance swimming. Contrary to the current literature, the catch position did not differ between swim groups, but did change in between swim paces. This finding challenges the existing knowledge of the catch position and requires further examination.

Finally foot ROM changed between sprint and distance paces. The literature has advocated that this occurs due to the energy requirements of the race distance (Adrian et al., 1966). The magnitude of hip and shoulder roll appeared to be strongly influenced by the contribution of the leg kick between paces.

Although the group as a whole did not change some particular kinematic or linear kinetic variables between paces, it was evident that a number of individuals adjusted their technique between paces in order to optimise their individual performance. This underlines the individualistic nature of swim performance.

6.3. Practical Implications

This study revealed that SG and DG are not distinctively different over a broad range of stroke variables. One of the primary differences was that the SG had a shorter pull phase duration than the DG at both paces. Because a shorter stroke phase duration has been associated with a greater hand speed, coaches should encourage those who tend to specialise in sprint events to execute a fast pulling action of the hand during this phase, regardless of the event distance in training. In order to execute a relatively fast pulling action, sprint swimmers should include specific strength exercises which target those muscles utilised in the pull phase, such as the lattisimus dorsi, rotator cuff and biceps. Land based stretch cord sessions are useful for developing these isolated muscles by mimicking the stroke pattern, in particular, by repeatedly performing the pulling action at a high intensity. Moreover, as sprinters begin to fatigue, whether in pool or land sessions, maintaining a fast contraction during the pull phase should be emphasised. Additionally, when all swimmers partake in the same training set, then the coach should be attentive to observe the sprinters executing a more powerful or rapid pulling action than the distance swimmers. However, it should be highlighted that distance swimmers should not be trained to perform the pulling action slower than the sprinters. Whereas, due to the powerful nature of sprint swimming, it is proposed that the execution of a fast pulling action is as a result of how they train for their specific event.

The other main difference found between SG and DG was the sequential ordering of the shoulders and hips rotating during the body roll. This finding that swimmers adjust the order of rotation between these segments is innovative and requires further examination. Currently coaches give importance to the skill of body rolling in front crawl swimming through drills in the pool and on land. However, drills that encourage a two-part roll are largely non-existent. Certainly within the teaching education modules provided by the British Amateur Swimming Association, no reference is made with regard to a two-part body roll, or a possible temporal sequencing of the shoulders and hips. This study supports that the shoulders and hips roll independently, and their temporal sequencing are dependent upon pace and group. Therefore, although it appears that swimmers have naturally adopted these characteristics, guidance through coach education is required to further develop the skill of rolling in front crawl swimming and how this action changes according to swim speed. This means that drills which encourage a two-part sequencing of the shoulders and hips should be included within all swimmers' training programs, regardless of the level or ability of the swimmer. Moreover, varying the sequencing order of the shoulders and hips through drill practice should also be implemented into training programs knowing that this relationship appears to change dependent on pace. Possibly including the participation of other sports, such as golf, boxing, etc, which encourage sequential rotations of the shoulders and hips could be effective in the development of this skill. In terms of specifically training sprint swimmers, coaches should emphasise that the hips rotate prior to the shoulders, whereas distance swimmers rotate the shoulders prior to the hips.

Although this study only revealed the above differences between SG and DG, it was further highlighted that, regardless of the race specialisation of the swimmer, sprint and distance swimming displayed distinctive stroke characterises. Sprint swimming, relative to distance, was characterised by a greater V_{av}, SF, SI but smaller SL; a greater extension and consequently range of the elbow angle throughout the push phase; a shorter entry phase duration and a longer pull, push and recovery phase duration; a greater vertical displacement of the foot. Therefore, when training swimmers for a sprint event or during a sprint set in training, coaches should focus on a high turnover rate of the arms and not a long stroke, in addition to reinforcing the other stroke characteristics. In order to encourage swimmers to execute a greater elbow extension during the push phase, coaches should promote aquatic drills which emphasise this characteristic in training. Such drills include doggy paddle with the swimmers head in the water, repeatedly performing only the push phase of the SC; single arm drills with the swimmers focus placed on a rapid extension at the end of each stroke. Land based activities would be centred towards the development of the triceps muscle group, such as using stretch cords, tricep dips, or tricep pull downs. Because sprint swimming displays a greater magnitude of vertical displacement of the feet, coaches should also emphasise a deeper kicking action whilst maintaining speed, instead of a standard kicking depth across all swim speeds.

Distance swimming, relative to sprinting, was characterised by a longer SL, but reduced V_{av}, SF and SI; an increased rotation of the shoulders and hips; a longer duration of the entry phase and a shorter duration of the pull, push and recovery phases; a reduced magnitude of the kicking vertical displacement. Therefore the primary goal for coaches when training distance sets should be to encourage a longer stroke and less turnover of the arms than sprint swimming. Coaches should also include more drills to develop a greater magnitude of shoulder and hip rotation and emphasis placed on a reduced kicking depth than that seen when doing sprint sets.

In conclusion, this study suggests that sprint and distance swimmers are not distinctively different in terms of stroke kinematics or kinetics when swimming at a sprint or distance pace. However, coaches should be aware that they do differ in terms of the duration of the pull phase and the sequential ordering of the shoulders and hips. Consequently, coaches should include specific drills to develop these characteristics and to place emphasis on those throughout the training session. Otherwise, coaches can be confident that sprint and distance swimmers are not as different in terms of technique as once suspected. However, this study also reveals that all swimmers display certain kinematic and kinetic characteristics associated distinctively with sprint and distance swimming. Coaches should be aware of sprint and distance swimming techniques and that all swimmers appear to adjust these characteristics in order to optimise their performance. Moreover, coaches may wish to consider the duration of various speed sets which are not necessarily appropriate to a sprint or distance swimmer, due to the associated changes made, which could in the long term promote unwarranted adaptations of a permanent nature.

6.4. Limitations and Recommendations

This study recruited sprint (50m) and distance (400m) specialist swimmers and found that these groups did not differ in terms of stroke characteristics to the extent expressed in the literature. However it is speculated that differences in stroke characteristics would be more pronounced if the groups were further apart on the spectrum of race distance specialisation. Therefore, it is possible to speculate that had the distance group been specialised 800-1,500m swimmers, that more marked and obvious differences relative to the sprint group may have emerged from this study.

This study aimed to examine how specialised sprint and distance swimmers change their stroke characteristics when swimming at a distance (400m) and sprint (25m) pace respectively. However to advance our understanding of how swimmers adjust their stroke dependent on swim velocity, all competitive paces should be examined. Front crawl events include 50m, 100m, 200m, 400m, 800m, 1,500m and most recently 10,000m. Therefore, to provide a true representation of swimming adjustments, all of the aforementioned paces should be tested. In doing so, this would provide useful information to coaches as to how swimmers change their technique when swimming at different paces, which is the standard practise in any training session. This information may influence the coaches’ decision to include various speeds sets, or question the duration of varied intensity sets.

This study focused on the biomechanical adjustments of swim technique made depending on the swim pace. What has been overlooked is the question: ‘why do these changes occur?’ or ‘what is the mechanism responsible for these changes?’ Such knowledge is essential to enhance the understanding of the technical adjustments which are dependent on swim speed. It is suggested that the data and results obtained from this study, may be examined from a motor control perspective in order to shed light on the aforementioned questions. In particular, the application of the dynamical systems theory which has frequently been used to analyse athletic performance across many sports, (due to its emphasis on processes of coordination and control in human movement systems) may prove useful (Bartlett et al., 1996; Glazier et al., 2002).

The criteria for trimming each video file of the swimmers' performances was to capture one complete SC. Due to the length constraints of the calibration frame, it was not always possible to capture a SC that commenced with the same hand entry. This had many consequences. Firstly, it has been reported in the literature that swimmers display a dominant and non-dominant arm when swimming which also means that one arm pulls stronger than the other. Because each SC did not begin with the same arm consistently, this may explain the large SD with regard to the timing variables in relation to the kinetic data. Secondly, it may have affected the duration of stroke phase calculations, since the 'first' and 'second' arm entry were considered. Thirdly, the occurrence of the shoulder and hip roll magnitudes had to be adjusted post analysis so that the left or right side was consistent throughout. To eliminate those problems, and to capture consistent data, it may have been better to collect 25m trials at a distance pace, and not the 400m straight, so that if a complete SC with the same hand entry did not occur, then it could be discarded and repeated without fatiguing the participant.

In this study, asymmetry was evident in relation to shoulder and hip roll, elbow angle extension and the majority of kinetic variables. The intention of this study was not to examine the laterality of the participants, since skilled swimmers are assumed to display a symmetrical stroke pattern (Nikodelis et al., 2005), however it was evident that all swimmers displayed an asymmetric stroke pattern. Therefore further analysis, taking into consideration lateral symmetry, should be conducted to evaluate the changes in kinematics and linear kinetics between sides when front crawl swimming at different velocities.

Front crawl is the fastest swim stroke, the most used in training programs and perhaps the most researched stroke. This study focused on the stroke changes made in front crawl swimming over two swim paces. However it is important that more studies of a similar nature are conducted across the remaining three strokes (butterfly, backcrawl and breaststroke) in order to develop our knowledge and understanding of all swimming strokes and how they change across paces.

Some individuals significantly adjusted their technique between paces, with respect to certain kinematic variables. Due to the small number of participants and a lack of consistency in the direction of change amongst individuals, further investigation is required that includes a larger sample and a greater number of trials to examine individual and group effects more closely. Moreover, because some variables approached significance, it is speculated that perhaps with a larger sample, and/or increased number of trials, significant differences may be found. Also, while there appeared to be some connections among variables that changed across groups and paces, regression and correlation analysis should be conducted with a larger sample than the current sample, to establish effects of change in one variable on the other variable.

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Appendix A

Subject	Age (years)	Height (cm)	Weight (kg)	Sprint/Distance Specialist	50m P.B (secs)	400m P.B. (mins)
1	17	176.4	70.9	Distance	25.80	4.01.98
2	18	180.5	72.6	Sprinter	24.46	4.12.96
3	16	176.8	63.1	Distance	28.04	4.10.31
4	16	179.6	76.2	Distance	24.90	4.04.52
5	20	194.2	82.2	Sprinter	24.58	4.01.42
6	15	184.8	71.3	Sprinter	24.60	4.15.98
7	23	198.8	94.5	Distance	23.92	3.48.56
8	18	181.9	75.6	Distance	24.50	3.55.12
9	19	183.0	79.1	Sprinter	24.60	4.20.39
10	22	176.3	66.0	Sprinter	24.49	4.06.47
11	18	184.6	69.4	Distance	24.70	3.59.95
12	17	191.1	83.8	Sprinter	24.24	N/T
13	15	180.9	60.3	Distance	N/T	4.03.84
14	17	180.7	75.7	Sprinter	24.17	4.27.32
15	17	175.7	68.1	Distance	25.99	4.08.41

Table AP.1: Swimmer’s performance measures.

Appendix B

Volunteer Information Sheet

Effects of 50m and 400m Race Paces on Three-Dimensional Kinematics and Linear Kinetics of Sprint and Distance Front Crawl Swimmers

Purpose of the Study:

Competitive swimmers tend to specialise in either sprint or distance events. Despite this acknowledgment, coaches often devise training programs that incorporate both varying distances and intensities. This accepted practice is considered justifiable in order to advance certain physiological aspects of the swimmer's physical condition. Recent studies have revealed that swimmers naturally adjust aspects of the stroke cycle depending on the swim velocity. However, the possible effect this practice may have on the stroke kinematics has previously not been investigated.

It has also been suggested that sprint and distance swimmers utilise distinct characteristics and stroke patterns in order to achieve optimal performance for their specific event. These parameters have not yet been thoroughly examined three dimensionally.

It is therefore important to extend this area of research to identify an optimal stroke pattern and kinetic characteristics which are uniquely appropriate to sprint and distance swimming. Such knowledge is necessary to help coaches direct a sprint or distance swimmer to an ideal pattern which is most effective for their particular event. Of great interest is to investigate if either group adjusts their stroke pattern when swimming at the non-preferred swim velocity, as may be the case during training. At this velocity it is unknown if either group exhibit similar stroke patterns to that of their preferred velocity, or whether they adjust their stroke pattern to resemble that of a sprint of distance swimmer.

Therefore, the purpose of this study is to identify the distinct kinematic and kinetic differences between sprint and distance swimmers. And to investigate if and how these specific stroke patterns vary in relation to the speed they are swimming.

What is expected of you?

Your participation will span over one single day and will not interfere with your training schedule. The participant will be required to swim four repeats of 25m and one 400m at maximal race pace. The order in which the swimmer performs these swims will be randomly assigned. A substantial period of recovery will be applied between all swims. Prior to the session, the swimmer will be instructed to perform a pre-competition warm-up.

Swimmer	Day One	
	4 x 25m	400m
Sprinter A	1	2
Sprinter B	2	1
Distance A	1	2
Distance B	2	1

Table 1: A sample outline of the participants' requirements within the study. The numbers '1' and '2' determine the order of the individual swims, i.e. the number in the 25m and 400m column determines the order the swims are performed.

During each swim the participant will videotaped, so that they may be subsequently analysed. In order to aid the motion analysis procedure, each participant will be marked with black theatrical paint (applied with a sponge) to the necessary joint and anatomical landmarks.

You will be required to wear a swim cap during each swim (this will be provided). You should wear fitted trunks as opposed to training shorts so that the hip can be easily identified.

During the calibrated area, the participant will be asked to hold their breath during alternative lengths, so that the act of breathing does not interfere with the stroke kinematics.

The approximate time duration is less than 45mins.

Possible Risks:

The primary objective throughout these testing sessions is to expose you to the minimalist risk possible. 'Minimal risk' means that you should not be exposed to a greater risk factor than the one you experience during your existing training sessions. If you feel during any of the testing sessions, that your exposure to any risk is greater than a normal training session, which you are uncomfortable with, then you are free to withdraw at any stage.

Benefits for you Participation?

You will have the opportunity to receive important feedback with regards to your swims, i.e. you can observe from the analysed data the effect of swimming at different velocities has on your stroke pattern and overall performance.

On completion of the study, the results and findings will be forwarded to the participant and relevant coach.

Notices

This research study will be conducted in the St Leonard's Swimming Pool.

It should be stated that you are under no obligation to complete these testing sessions, and are at liberty to withdraw at anytime.
All information obtained will remain strictly confidential and anonymous, except if any of the individuals participating in the study wish to observe their data. When publishing the study, no names will be referenced, or any information in association to the individuals. When the study is completed, all video footage will be erased and any other material collected that would reveal the identity of any of the persons involved.

If you have any further questions with regard to this study or about the above information, please no not hesitate to contact the research project supervisor or myself (details provided below)

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Informed Consent Form

______________________________ **(Please Print Your Name)**

Please tick the appropriate box: **YES** **NO**

1. I have read and understood the Volunteer Information Sheet, which outlines the details and requirements of this study.

2. I fully understand the procedures of this study, my Participation within it and have no further questions.

3. I understand that video recording is a fundamental element to the study and I grant my permission for their implementation.

4. I also grant my permission for the video recordings to be shown to others for educational purposes, for example on the world-wide web.

5. I understand that I am free to withdraw from the study at any time.

6. I give consent for my participation in the study.

____ ____________________

Signature of the Participant **Date**
(or parent/guardian of child under 16yrs)

____ ____________________

Signature of the Investigator **Date**

Pre-Activity Questionnaire

Sprint vs. Distance Swimmer Analysis

Name ______________________

Date of Birth________________ Age ______________

Please tick the appropriate box: **YES** **NO**

Has the test procedure been fully explained to you?

Any information contained herein will be treated as confidential

1. Has your doctor ever said that you have a heart condition and that you should only do physical activity under the doctor's instruction?
2. Do you feel pain in your chest when you do physical activity?
3. In the past month have you had chest pain when you were not doing physical activity?
4. Do you lose your balance because of dizziness or do you ever lose consciousness?
5. Do you have a joint or bone problem that could be made worse by a change in your physical activity?
6. Is your doctor currently prescribing drugs for blood pressure or heart condition?
7. Do you know of any other reason why you should not undergo physical activity?

If you have answered **NO** to **all** questions then you can be reasonably sure that you can take part in the physical activity required of the test procedure.

I ____________________________________declare that the above information is correct at the time of completing this questionnaire.

Date ______________ Signature of Supervisor: ________________

Appendix C

Marker	Side View Marker Location	Frontal View of Marker Location
Vertex	Highest point of the head above the ear	Central highest point of the head
C2	Mandible Angle	Centre of chin
C7	At level of C7 spine, in centre of neck segment	Adam's Apple
AC Joint	One marker at AC joint should be visible in both views	One marker at AC joint should be visible in both views
Humerus Head	Greater tubercle of the humerus (head of humerus)	Same as side view marker but on the midline of the arm
Elbow	Olecranon Process of Ulna	Level of the Olecranon Process of the Ulna
Wrist	Wrist	Level with the side marker
Finger	Longest tip of the 3rd Distal Phalanx	Longest tip of the 3rd Distal Phalanx
Xiphoid	Level with front marker, on the midline of the trunk.	Base of Sternum
Pubic	Not required	Applied by participant
Hip	Greater Trochanter of Femur	Level with the side view marker, on the midline of the thigh.
Knee	Level to the side of the Patella	Centre of Patella
Ankle	Lateral Malleolus of the Fibula	Level with the side marker, on the midline of the ankle.
Metatarsal phalangeal joint P 5	5th Metatarsophalangeal joint	Same as side view
Toe	1st Interphalangeal joint (Tip of big toe)	1st Interphalangeal joint (Tip of big toe)

Table AP.2: Location of anatomical landmarks for eZone calculations.