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Effect of Fatigue on Three-dimensional Kinematic Characteristics of Elite and Sub-elite Swimmers During Maximal Intermittent Exercise

The University of Edinburgh

Thesis submitted for the degree of Master of Philosophy

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Submitted to The University of Edinburgh:
October, 2016
Abstract

Exercise-induced fatigue constitutes an important limiting factor for sports performance. In swimming biomechanics, studies have examined the effect of fatigue-induced changes in kinematic variables associated with swim performance. However, as the vast majority of those studies have tested swimmers over race distances, there is a lack of data regarding changes in kinematic parameters during maximal intermittent training sets (a common method used by coaches in order to create physiological adaptations to delay the onset of fatigue). Furthermore, little is known with regard to possible different technical adjustments between swimmers of different skill level during this type of training sets. The identification of distinct kinematic parameters in different skill levels will advance the knowledge and understanding of the kinematical/technical adaptations under fatigue conditions. Therefore, the aim of the present study is to investigate the effect of fatigue on the three-dimensional (3D) kinematic characteristics of elite and sub-elite swimmers during a maximal intermittent training set.

Sixteen male sprint swimmers of national/international level volunteered to participate in the study. The swimmers, were assigned to elite or sub-elite group based on their skill/performance level: elite, 8 swimmers whose personal best time in 100-m front crawl equal at least that of the 90% of the World Record; sub-elite, 8 swimmers whose personal best time in 100-m front crawl slower than 90% of the World Record). The swimmers, performed 12 maximal 50-m trials (work to rest ratio 1:1.5) which were recorded with the use of 6 synchronised cameras (4 underwater and 2 above water) sampling at a frequency of 25 fields/second. A non-breathing stroke cycle through a 6.75 m³ calibrated volume was analysed every second trial, starting from the first one (trials 1, 3, 5, 7, 9 and 11). Anthropometric data were obtained with the use of the e-Zone method. All selected stroke cycles were processed using APAS software for the acquisition of the 3D coordinates. The following kinematic variables were calculated: average horizontal velocity (V), stroke length (SL), stroke frequency (SF), stroke index (SI), relative duration (percentile of stroke cycle duration) of stroke phases (entry, pull, push, release, recovery), shoulder and hip roll angles, absolute and relative (percentile of V) intracycle velocity variations (IVV) in horizontal (IVVx and IVVy%), vertical (IVVy and IVVz%) and lateral (IVVz and IVVz%) axes. Two-way ANOVAs (trial x skill level) with repeated measures was performed to compare elite and sub-elite groups across the trials. V and SL decreased significantly (5.3% and 4.9% respectively) throughout the trials as a result of fatigue, while SF remained unchanged. Elite swimmers displayed significantly larger V, SL and SI values across the trials, while SF values were not different between groups. As fatigue developed, the elite swimmers managed to maintain a more constant V and SI by minimising the reductions in their SL. For all swimmers the duration of entry phase remained constant throughout the trials, the duration of pull and push phases increased in trials 5 and 7 before they decreased in trials 9 and 11, while, conversely, the duration of the release and recovery phase decreased in trials 5 and 7 and decreased in trials 9 and 11. Across the trials, the elite swimmers spent significantly longer time in pull and push phase and shorter time in entry, release and recovery phase. Also, as the trials progressed, the elite swimmers adjusted their technique in order to increase the time spent in pull and push phases by reducing the time spent in entry, release and recovery phases. The shoulder and hip roll angles increased for all swimmers during the trials, with the sub-elite swimmers rolling their hips significantly more, whereas no differences between groups in shoulder roll angles were observed. The sub-elite swimmers also significantly increased their hip roll in trials 9 and 11. IVVx decreased during the trials, while IVVx, IVVy, IVVz and IVVz% remained unchanged. The elite group displayed significantly larger IVVx, IVVx% and IVVy, while showed smaller IVVz%.

In conclusion, the development of fatigue affected significantly performance-related kinematic parameters of all swimmers. The most marked fatigue-induced kinematic changes were observed in the sub-elite swimmers, while the elite swimmers maintained better their technique by making technical adjustments to maintain their V. It is suggested that coaches should monitor the technical elements of their swimmers during maximal intermittent training sets in order to prevent serious impairments in technique. Especially for sub-elite swimmers, this type of training sets should not exceed 300-400 m at a time.
Lay summary

Exercise-induced fatigue constitutes an important limiting factor for sports performance. In swimming, studies have examined the effect of fatigue in swimming technique. However, as the vast majority of those studies have tested swimmers over race distances, there is a lack of data regarding changes in kinematic parameters during maximal intermittent training sets (a common method used by coaches in order to delay the onset of fatigue). Furthermore, little is known with regard to possible different technical adjustments between swimmers of different skill level during this type of training sets. The identification of distinct technical characteristics in different skill levels will advance the knowledge and understanding of the technical adaptations under fatigue conditions. Therefore, the aim of the present study is to investigate the effect of fatigue on the swimming technique of elite and sub-elite swimmers during a maximal intermittent training set.

Sixteen male sprint swimmers of national/international level volunteered to participate in the study. The swimmers, were assigned to elite or sub-elite group based on their skill/performance level. The swimmers, performed 12 maximal 50-m trials which were recorded with the use of 6 synchronised cameras (4 underwater and 2 above water). The swimming technique was analysed every second trial, starting from the first one (trials 1, 3, 5, 7, 9 and 11). The following parameters related to technique were calculated: average velocity (V), stroke length (SL, horizontal distance that the body travels between two hand entries of the same hand/full stroke cycle), stroke frequency (SF, the number of full stroke cycles performed within the unit of time), stroke index (SI, product of V and SL), duration over which swimmers produce propulsive forces to the water (propulsive phase), shoulder and hip roll angles, absolute and relative (percentile of V) velocity fluctuations during a stroke cycle in horizontal, vertical and lateral axes.

V and SL decreased significantly (5.3% and 4.9% respectively) throughout the trials as a result of fatigue, while SF remained unchanged. Elite swimmers displayed significantly larger V, SL and SI values across the trials, while SF values were not different between groups. As fatigue developed, the elite swimmers managed to maintain their technique better. For all swimmers, the duration of propulsive phase increased until trial 7 before it decreased in trials 9 and 11. Across the trials, the elite swimmers’ propulsive phase was significantly longer compared to the one of the sub-elite swimmers. Also, as the trials progressed, the elite swimmers adjusted their technique in order to increase the time spent in propulsive phase by reducing the time spent in the non-propulsive phase. The shoulder and hip roll angles increased for all swimmers during the trials, with the sub-elite swimmers rolling their hips significantly more, whereas no differences between groups in shoulder roll angles were observed. The sub-elite swimmers also significantly increased their hip roll in trials 9 and 11. All swimmers decreased the absolute magnitude of horizontal velocity fluctuation during the trials, while the magnitudes of relative horizontal velocity fluctuation and the absolute and relative vertical and lateral velocity fluctuations remained unchanged. The elite group displayed significantly larger horizontal (absolute and relative) and vertical (absolute) velocity fluctuations, while showed smaller relative lateral velocity fluctuations in relation to the sub-elite swimmers.

In conclusion, the development of fatigue affected significantly the technique of all swimmers. The most marked changes in technique were observed in the sub-elite swimmers, while the elite swimmers maintained better their technique by making technical adjustments to maintain their V. It is suggested that coaches should monitor the technical elements of their swimmers during maximal intermittent training sets in order to prevent serious impairments in technique. Especially for sub-elite swimmers, this type of training sets should not exceed 300-400 m at a time.
Declaration

Effect of Fatigue on Three-dimensional Kinematic Characteristics of Elite and Sub-elite Swimmers During Maximal Intermittent Exercise

Thesis submitted for the degree of Master 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: _________________
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List of abbreviations

%COM Segment’s centre of mass position as percentile of segment’s length
%WR Percentile of the world record time
2D Two-dimensional
3D Three-dimensional
95% CI 95% confidence intervals
ANOVA Analysis of variance
APAS Ariel performance analysis system
ATP Adenosine triphosphate
CGM Central governor model
cm Centimetres
CNS Central nervous system
COM Centre of mass
CV% Percent coefficient of variation
df Degrees of freedom
DLT Direct linear transformation method
EMG Electromyography
FC Front crawl
FINA Federation Internationale De Natation
Hz Hertz
ICC Intra-class correlation coefficient
IVV Intracycle velocity variations
IVV% Intracycle velocity variation as percentile of average horizontal velocity
kg Kilograms
m Metres
min Minutes
p Probability level (α)
PB Personal best time
r Pearson’s product moment correlation coefficient
s Seconds
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<td>SPSS</td>
<td>Statistical package for social sciences</td>
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1. Introduction

1.1. Background

Sports performance is the combined result of coordinated exertion and integration of a variety of factors (Astrand et al., 2003). These factors can be divided into three categories: trainable factors (biomechanical, physiological, and psychological); teachable factors (tactics) and others outside the control of the athlete and coach (genetics). Exercise-induced fatigue constitutes an important limiting factor of sports performance and has been linked with all the aforementioned performance-related categories (Abbiss and Laursen, 2005; Millet, 2011). Typically, fatigue is defined as the reduction in maximal power output (Bishop, 2012) and in swimming the development of fatigue has been associated with reductions in effective mechanical power output which results in decreased swimming velocity (Toussaint et al., 2006).

Given its link with performance, fatigue in swimming has been widely investigated by assessing kinematic/biomechanical parameters, such as mechanical output, electromyography (EMG), swimming velocity, stroke length, stroke frequency, spatiotemporal parameters, arm coordination; physiological parameters, such as blood lactate concentration, energy cost, heart rate, oxygen consumption; and psychological factors, such as perceptions of fatigue (Alberty et al., 2005; 2008; 2009; Aujouannet et al., 2006; Bassan et al., 2016; Bonifazi et al., 1993; Chollet et al., 1997; Conceição et al., 2014; de Jesus et al., 2015; Dekkerle et al., 2015; Figueiredo et al., 2011; 2012a; 2013b; Ikuta et al., 2012; Kennedy et al., 2013; Komar et al., 2012; Laffite et al., 2004; Lomax et al., 2015; Psycharakis et al., 2008; 2010; Schnitzler et al., 2011; Seifert et al., 2007a; Stirn et al., 2011; Suito et al., 2008; Tella et al., 2008; Toussaint et al., 2006). These studies indicate that fatigue in swimming has been analysed with the use of
various methodologies. It is evident that the investigation of fatigue provides useful knowledge in the direction of a holistic understanding of this important topic.

An important trainable factor that swimmers aim to improve upon is to delay the development of fatigue (Maglischo, 2003). For that reason, swim coaches design specific training sets for creating such physiological adaptations (reducing the rate of lactate production, removing the lactate from working muscle fibres, improving buffering capacity) in order to delay the onset of fatigue and the deterioration of performance (Maglischo, 2003). Intermittent training sets at race pace and/or race stroke frequency are popular amongst swim coaches to create the aforementioned physiological adaptations (Alberty et al., 2008; Maglischo, 2003). Training sets of 300-800 m at race pace and/or stroke frequency have been suggested for improving the performance in 100-m events for all 4 competitive strokes (Maglischo, 2003) and are used on a daily basis as part of swimmers’ preparation. However, no studies have examined the effect of fatigue during such maximal training sets. This information is important in terms of detailing whether swimmers adjust their technique as a consequence of the development of fatigue via a maximal training set. Currently fatigue studies in relation to stroke kinematics have only focused across race distances during competition or race simulations (Alberty et al., 2005; Bonifazi et al., 1993; Chollet et al., 1997; Conceição et al., 2014; Figueiredo et al., 2011; 2012a; 2013b; Ikuta et al., 2012; Laffite et al., 2004; Lomax et al., 2015; Psycharakis et al., 2010; Schnitzler et al., 2011; Seifert et al., 2007a; Stirn et al., 2011; Suito et al., 2008; Toussaint et al., 2006), incremental tests to exhaustion (de Jesus et al., 2015; Komar et al., 2012; Psycharakis et al., 2008), continued maximal efforts to exhaustion (Alberty et al., 2008; 2009; Bassan et al., 2016), submaximal efforts (Dekerle et al., 2015) and maximal low-volume (125-200 m) intermittent sets (Aujuannet et al., 2006; Tella et al., 2008). Thus, the effect of fatigue on performance-related parameters during maximal intermittent training sets of higher volume than the race distance (i.e. 300-800 m in order to create physiological adaptations as suggested by Maglischo, 2003) is yet to be investigated.
Average swimming velocity (V) is the best measure of swimming performance (Craig et al., 1985) and equals the product of stroke length (SL: the distance covered during a complete stroke cycle) and stroke frequency (SF: the number of stroke cycles per minute). In swimming biomechanics, researchers have focused primarily on the interrelationship between SL and SF (Toussaint et al., 2006). Also, other kinematic parameters linked to V, SL and SF have attracted the attention of researchers. These parameters include stroke index (SI), the duration of propulsive and non-propulsive phases of the stroke cycle, the intracycle velocity variations (IVV) and the body roll (Arellano et al., 1994; Costill et al., 1985; Figueiredo et al., 2012a; 2012b; 2013a; Pelayo et al., 1997; Seifert et al., 2007a; Pscharakis et al., 2010). A number of studies have attempted to compare swimmers of different skill level with respect to performance-related kinematic parameters in order to identify differences in those kinematic parameters which account for the discrimination in skill/performance level (Chollet et al., 1997; Craig et al., 1985; D’Acquisto and Costill, 1998; Leblanc et al., 2007; Schnitzler et al., 2010; Seifert et al., 2010a; Takagi et al., 2004). However, the effect of skill level on some kinematic parameters (such as IVV) during maximal training sets has not been adequately studied and/or the results remain controversial. Furthermore, in some studies elite swimmers have been compared to recreational or regional-level ones (Chollet et al., 1997; Leblanc et al. 2007; Schnitzler et al. 2010; Seifert et al., 2010a) and therefore the value and generalization of the results are limited. Data with respect to distinct kinematic characteristics associated with performance and skill level will allow swim coaches to design more effective training focusing on specific technical characteristics.

In swimming research, video-based motion analysis is commonly used for the assessment of the kinematic characteristics of the swimmers. The studies in which video-based techniques have been used can be divided into 3 categories: race analysis (Arellano et al., 1994; Craig et al., 1985; Kennedy et al., 1990; Mason and Cossor, 2000); two-dimensional (2D) motion analysis (Chollet et al., 2000; Schnitzler et al., 2010; Seifert et al., 2004; 2005; 2007a; 2007b;
2010a; 2010b) and three-dimensional (3D) motion analysis (Cappaert et al., 1995; Figueiredo et al., 2012a; 2012b; 2013a; McCabe et al., 2011; Psycharakis et al., 2010). Race analysis has been used due to the fact that immediate feedback on basic kinematic variables (such as V, SL and SF) can be given to swimmers and coaches. However, the accuracy of the results obtained from this technique is questionable as the kinematics of the centre of mass (COM) are not reflected (Fernandes et al., 2012; Figueiredo et al., 2009; Psycharakis and Sanders, 2009). More accurate results can be obtained by 2D motion analysis as this method allows calculation of the kinematic variables based on the COM profile. Nonetheless, 3D motion analysis is considered the most accurate method for the determination of the kinematic parameters of the COM (Psycharakis and Sanders, 2009), since the swimming technique involves all three axes (horizontal, vertical, lateral). Indeed, 3D underwater motion analysis allows the individual and quantitative evaluation of swimming performance, disclosing the potential to improve the movement pattern efficiency of the swimmers and their performance in competition (Silvatti et al., 2013). At present, no studies using 3D motion analysis methods have assessed the effect of fatigue and skill level on kinematic characteristics during a maximal intermittent training set.

1.2. Aim of the study

The aim of this study is to determine the effect of fatigue on the 3D kinematic characteristics of elite and sub-elite male sprint swimmers during a maximal intermittent training set in order to highlight distinct technical characteristics that could account for the swimming performance.

1.3. Purposes of the study

1. To investigate the adaptations in the kinematic characteristics of male sprint swimmers during a maximal intermittent training set.
2. To determine whether there are kinematic characteristics accountable for the different skill level/performance between elite and sub-elite male sprint swimmers.

3. To examine whether elite and sub-elite male sprint swimmers are affected differently by fatigue depending on their skill levels.

It was hypothesised that:

a) the performance-related kinematic parameters of the entire population of swimmers would be altered during the course of a maximal intermittent training set;

b) kinematic variables accountable for the discrimination of performance level would be identified; and

c) over the course of the training set, the elite swimmers would be more capable of maintaining the kinematic characteristics related to performance in comparison to the sub-elite swimmers.
2. Literature review

This study examines the effect of swimming-induced fatigue on the kinematic characteristics of swimmers of different skill levels. As a meaningful context within which to carry out the study, literature in relation to fatigue and its mechanisms is reviewed and literature related to the kinematical variables associated with swimming performance is presented.

2.1. Exercise-induced fatigue

2.1.1. Definition of fatigue

Scientists have made several attempts to accurately define fatigue. One of the most representative definitions has been suggested by Bigland-Ritchie and Woods (1984) who expressed fatigue as ‘any reduction in the force generating capacity of the total neuromuscular system regardless of the force required in any given situation’. In the context of swimming, the impairment of performance due to fatigue has been linked to the reduction in maximal power output which leads in decreased swimming velocity (Toussaint et al., 2006).

Fatigue is considered an inevitable and negative consequence of physical exercise and a well-known limiting factor of athletic performance (Abbiss and Laursen, 2005). Research on fatigue-induced impairments in performance spans different sport science disciplines, namely biomechanics, physiology and psychology. A biomechanist may view fatigue as a reduction in the force output of a muscle concomitant with changes in biomechanical/kinematical parameters, a psychologist may see fatigue as a sensation of tiredness, whereas a physiologist may define fatigue as the failure of a specific physiological system (Abbiss and Laursen, 2005). Fatigue is a process while exhaustion is the endpoint of this process. The present study
focuses on the biomechanical/kinematical changes as a consequence of the development of fatigue to exhaustion levels.

Fatigue can be of central (proximal to the motor unit) or peripheral origin (within the local motor unit). The processes inside the spinal cord and head are defined as central, while the processes in the peripheral nerve, neuromuscular junction and muscular system are defined as peripheral (Allen et al., 2008). In the case of central fatigue, the central nervous system (CNS) is not able or willing to request such a great output. In other words, the CNS displays an inability to activate the motor pathway to the extent expected, anticipated or required to carry out a given task (MacIntosh and Rassier, 2002). In this context, central fatigue refers to an impaired ability of the CNS to recruit motor units at higher discharge rate (Millet, 2011). On the other hand, more commonly, the performer’s inability to produce adequate power during the course of a task is related to the fatigued muscles (MacIntosh and Rassier, 2002). In most cases during exercise, the central and peripheral origin of fatigue coincide, as during maximal muscle contractions there is, at least, a small degree of central failure. Nonetheless, since most of the fatigue-induced changes occur within the muscles, it has been universally accepted that isolated muscle tissues can be studied when the phenomenon of fatigue is investigated (Allen et al., 2008; MacIntosh and Rassier, 2002).

2.1.2. Mechanisms for understanding fatigue
Several models have been developed to describe the mechanisms by which fatigue occurs during exercise. Some of these models include: cardiovascular/anaerobic; energy supply/energy depletion; neuromuscular fatigue; muscle trauma; biomechanical; thermoregulatory; psychological/motivational; and central governor (Abbiss and Laursen, 2005).
The cardiovascular/anaerobic model of fatigue suggests that fatigue occurs when the heart is not capable of supplying sufficient oxygenated blood and removing waste products to and from the working muscles (Abbiss and Laursen, 2005). Although this model remains the most popular among scientists, the limitation of this model is that if the pumping capacity of the heart limits the oxygen supply to the working muscles, then the heart itself, and not the muscles, will be the first organ affected by any postulated oxygen deficiency (Noakes, 2000).

The energy supply/energy depletion model proposes that fatigue is a result of a limited supply of adenosine triphosphate (ATP) to the working muscles. This inadequate supply of ATP has been linked to a fuel substrate depletion, namely muscle and liver glycogen, blood glucose and phosphocreatine (Abbiss and Laursen, 2005).

According to the neuromuscular fatigue model, it is not the inadequate supply-rate of substrate (oxygen or fuel) to exercising muscles that limits athletic performance, but the processes related to muscle recruitment, excitation and contraction (Noakes, 2000).

Alternatively, the proponents of muscle trauma model suggest that the exercise-induced physical damage in the muscles affects the power-producing capacity of the working muscles. This is because prolonged exercise causes significant disruption to the muscle, resulting in alterations to intramuscular chemical homeostasis and activation of pain receptors, which, in turn, may cause a reduction in neuromuscular activation and/or reduced force production of the muscle (Abbiss and Laursen, 2005).

The biomechanical model is based on the idea that an improved efficiency of motion results in better economy. Consequently, it is hypothesised that an improved economy of motion will relieve other physiological mechanisms that may cause fatigue (Abbiss and Laursen, 2005).
The advocates of the thermoregulatory model suggest that increases in core body, muscle and skin temperature cause greater demands to be placed on other physiological systems/models that may be responsible for fatigue during prolonged exercise. Furthermore, the thermoregulatory model of fatigue proposes that a critical core body temperature may exist and the attainment of this temperature leads to a limitation in athletic performance (Abbiss and Laursen, 2005).

According to the psychological/motivational model, fatigue can be defined as a lack of enthusiasm or interest during exercise and is often included as a part of neuromuscular model of fatigue (Abbiss and Laursen, 2005). This model’s theory lies in the fact that, in literature, there is no apparent single physiological variable due to which alternations in motor output from afferent signals occur (Abbiss and Laursen, 2005). As a matter of fact, it is assumed that several physiological mechanisms are responsible for psychological alternations in central activation and perceived exertion, which in turn determine the unconscious perception of fatigue, leading to reductions in power output, and sometimes leading to exhaustion during prolonged exercise (Abbiss and Laursen, 2005).

Finally, the central governor model (CGM) holds that the CNS subconsciously estimates the metabolic cost required to complete a given task in order to avoid any harmful body failure. This model states that in all forms of exercise, the CNS regulates the extent of neuromuscular recruitment, anticipatively and continuously, according to responses in muscles, joints, body temperature, cardiopulmonary system and cognitive process (Pires, 2013). The CGM model supports that there is an interaction between physiological and psychological factors before the exercise starts. This interaction establishes athlete’s initial pace; athlete’s physiological state at the start of exercise; the anticipated distance and duration of the intended exercise bout; the degree of previous experience that the athlete has; the athlete’s level of motivation; and the athlete’s level of self-belief (Noakes, 2011).
Overall, the CGM model seems to be able to provide better explanations for different phenomena related to fatigue during exercise. That is because according to the CGM, exercise is considered as a behaviour that is regulated by complex systems in the CNS. The complexity of this regulation is impossible to be explained if the phenomena are studied as a collection of disconnected components, as is the usual approach in modern research studies (Noakes, 2011).

Nevertheless, the scope of this study is to investigate the athletes’ responses under fatigued conditions rather than to evaluate the aforementioned mechanisms/models. However, a brief review of the mechanisms which are related to the occurrence of fatigue may be useful for the interpretation of the results of the present work.

2.2. Swimming performance

The identification of variables that influence swim performance is one of the main topics in swimming science (Costa et al., 2012). Researchers have commonly assessed swim performance from an energetics/physiological and/or biomechanical perspective (Barbosa et al., 2010; Figueiredo et al., 2013a). However, this study will focus on examining biomechanical variables associated with swimming performance.

In competitive swimming, the main objective is to travel a given distance in the minimum time (Barbosa et al., 2010; Hay et al., 1993). With exception of starts and turns, the average swimming velocity (V) is the most important deterministic factor of the swimming performance (Barbosa et al., 2010).

2.2.1. Average swimming velocity

V has been defined as the product of stroke length (SL) and stroke frequency (SF) (Craig and Pendergast, 1979; Grimston and Hay, 1986):
\[ V = SL \times SF \]

where \( V \) is the average swimming velocity (expressed as m\( \cdot \)s\(^{-1} \)); \( SL \) represents the horizontal distance (m) that the body travels during a full stroke cycle (the period between two hand entries of the same hand); and \( SF \) is the number of full stroke cycles performed within a unit of time (cycles\( \cdot \)min\(^{-1} \) or Hz) (Barbosa et al., 2011). Thus, \( SL \) and \( SF \) are the most critical factors which determine swimming performance (Hay, 1993; Maglischo, 2003).

During competition, it has been found that both male and female swimmers, achieve the highest \( V \) in front crawl events, followed by butterfly, backstroke and breaststroke events (Craig et al., 1985; Kennedy et al., 1990). Table 2.1 shows some numerical findings from the U.S. Olympic Trials 1984 (Craig et al., 1985), Seoul Olympic Games 1988 (Kennedy et al., 1990) and Rio Olympic Games 2016 (internet source – www.tritonwear.com). As the present study focuses on well-trained male swimmers, only relevant data are reported in this table.

<table>
<thead>
<tr>
<th>Study</th>
<th>Participants</th>
<th>Event</th>
<th>( V ) (m( \cdot )s(^{-1} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Craig et al. 1985</td>
<td>Male</td>
<td>100-m front crawl</td>
<td>1.98 ± 0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100-m butterfly</td>
<td>1.83 ± 0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100-m backstroke</td>
<td>1.76 ± 0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100-m breaststroke</td>
<td>1.57 ± 0.01</td>
</tr>
<tr>
<td>Kennedy et al. 1990</td>
<td>Male</td>
<td>100-m front crawl</td>
<td>1.88 ± 0.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100-m butterfly</td>
<td>1.75 ± 0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100-m backstroke</td>
<td>1.69 ± 0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100-m breaststroke</td>
<td>1.52 ± 0.08</td>
</tr>
<tr>
<td><a href="http://www.tritonwear.com">www.tritonwear.com</a></td>
<td>Male</td>
<td>100-m front crawl</td>
<td>2.19 ± 0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100-m butterfly</td>
<td>2.08 ± 0.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100-m backstroke</td>
<td>1.96 ± 0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100-m breaststroke</td>
<td>1.81 ± 0.05</td>
</tr>
</tbody>
</table>

Table 2.1: Average swimming velocity (\( V \)) in 100-m events during competition. Data presented as mean ± standard deviation (SD).

In Table 2.1, the discrepancy in \( V \) values between the studies of Craig et al. (1985) and Kennedy et al. (1990) can be attributed to the different methods for \( V \) calculation that were employed in those studies. Indeed, in the former study \( V \) was overestimated as the effect of
start and turn phases was not taken into consideration. It is well known that swimmers achieve their fastest V at the start and turn phases (Thompson et al., 2000).

Despite the fact that V, SL and SF are widely measured during major swimming competitions and the data are often available on the internet (e.g. www.swim.ee - Haljiand, 2016), there is a lack of competition data in the form of published scientific studies. The aforementioned studies of Craig et al. (1985) and Kennedy et al. (1990), although provided valuable data, are dated and this fact constitutes a potential limitation with respect to the fact that the stroke kinematics may have changed since these studies were conducted. On the other hand, the race analysis data on the internet may not be entirely accurate as the methods by which the data were collected are unknown.

2.2.2. Stroke length and stroke frequency

The association of SL and SF with V and therefore with swimming performance has led researchers to investigate the interrelationship SL-SF during major competitions, in order to identify the principal components related to swimming performance (Arellano et al., 1994; Craig et al., 1985; Kennedy et al., 1990). Strong negative correlations between SL and SF were reported for both men and women by Arellano et al. (1994) in 50-m front crawl (r=-0.89 and r=-0.92 respectively), 100-m front crawl (r=-0.83 and r=-0.90 respectively) and 200-m front crawl (r=-0.86 and r=-0.94 respectively), and by Kennedy et al. (1990) in 100-m front crawl (r=-0.90 and r=-0.89 respectively), 100-m backstroke (r=-0.79 and r=-0.74 respectively), 100-m breaststroke (r=-0.87 and r=-0.79 respectively) and 100-m butterfly (r=-0.84 and r=-0.65 respectively), meaning that as V decreases from 50-m to 200-m events, SL increases and SF decreases. This indicates the interdependence between SL and SF, with the swimmers displaying high SL values concurrently with low SF values and vice versa. Additionally, it was reported that swimmers achieve similar V values by employing different combinations
SL and SF, which indicates that the relationship between SL and SF is highly individual (Pai et al., 1984; Pelayo et al., 1996).

Furthermore, high positive correlations for both genders have been found between SL and performance in 50-m (r=0.62 and r=0.49 for male and female respectively), 100-m (r=0.57 and r=0.64 for male and female respectively) and 200-m (r=0.55 and r=0.58 for male and female respectively) front crawl events (Arellano et al., 1994), highlighting the critical role of SL to successful performance. Indeed, SL has been proposed to be the single best predictor of performance in front crawl (Costill et al., 1985). However, Mason and Cossor (2000) reported no significant correlation between SL and final time in males’ front crawl events (50-200-m) in the Pan Pacific Swimming Championships.

Males and females seem to employ different race strategies with respect to variations of SL and SF across the front crawl events. Male swimmers increased their V in the shorter events compared to the longer ones by decreasing SL and increasing SF (Craig et al., 1985; Arellano et al., 1994), whereas the females increased V by increasing SF and maintaining a relatively constant SL. Table 2.2 presents SL and SF data of male swimmers from studies that determined those parameters during competitions.

<table>
<thead>
<tr>
<th>Study</th>
<th>Event</th>
<th>SL (m)</th>
<th>SF (cycles·min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Craig et al. 1985</td>
<td>100-m front crawl</td>
<td>2.24 ± 0.05</td>
<td>53.1 ± 1.3</td>
</tr>
<tr>
<td></td>
<td>100-m butterfly</td>
<td>2.05 ± 0.04</td>
<td>53.7 ± 0.9</td>
</tr>
<tr>
<td></td>
<td>100-m backstroke</td>
<td>2.21 ± 0.03</td>
<td>47.9 ± 0.8</td>
</tr>
<tr>
<td></td>
<td>100-m breaststroke</td>
<td>1.69 ± 0.05</td>
<td>56.4 ± 1.6</td>
</tr>
<tr>
<td>Kennedy et al. 1990</td>
<td>100-m front crawl</td>
<td>2.07 ± 0.23</td>
<td>52.8*</td>
</tr>
<tr>
<td></td>
<td>100-m butterfly</td>
<td>1.90 ± 0.16</td>
<td>54.0*</td>
</tr>
<tr>
<td></td>
<td>100-m backstroke</td>
<td>2.08 ± 0.13</td>
<td>47.4*</td>
</tr>
<tr>
<td></td>
<td>100-m breaststroke</td>
<td>1.58 ± 0.14</td>
<td>55.2*</td>
</tr>
<tr>
<td><a href="http://www.tritonwear.com">www.tritonwear.com</a></td>
<td>100-m front crawl</td>
<td>2.27 ± 0.06</td>
<td>52.3 ± 2.0</td>
</tr>
<tr>
<td></td>
<td>100-m butterfly</td>
<td>2.20 ± 0.05</td>
<td>53.7 ± 1.6</td>
</tr>
<tr>
<td></td>
<td>100-m backstroke</td>
<td>2.18 ± 0.09</td>
<td>49.2 ± 3.7</td>
</tr>
<tr>
<td></td>
<td>100-m breaststroke</td>
<td>2.05 ± 0.15</td>
<td>50.7 ± 4.5</td>
</tr>
</tbody>
</table>

Table 2.2: Average SL (m) and SF (cycles·min⁻¹) in 100-m events during competition. Data presented as mean ± SD, *SD not provided.
The fact that the non-swimming elements (start and turn) were not considered in the study of Craig et al. (1985) can explain the larger SL values reported in this study in relation to the values reported by Kennedy et al. (1990), as shown in Table 2.2.

Various anthropometric parameters such as body height (Arellano et al., 1994; Kennedy et al., 1990; Pelayo et al., 1996), arm and leg lengths (Grimston and Hay, 1986; Seifert et al., 2007a), arm span (Seifert et al., 2007a), axilla, hand and foot cross sectional areas and leg frontal area (Grimston and Hay, 1986) have been reported to influence the relationship between SL and SF and therefore V. Positive correlations for both sexes have been found in front crawl events between height-performance ($r=0.69$ and $r=0.55$ in 50-m; $r=0.75$ and $r=0.52$ in 100-m; $r=0.71$ and $r=0.50$ in 200-m for men and women respectively) and height-SL ($r=0.56$ and $r=0.46$ in 50-m; $r=0.58$ and $r=0.41$ in 100-m; $r=0.52$ and $r=0.35$ in 200-m for men and women respectively). Thus, height has been recognised as the dominant anthropometric parameter of success in front crawl events (Arellano et al., 1994; Kennedy et al., 1990), especially for male swimmers due to the very high correlations between height and performance. Although the link between height and SL is evident, in the vast majority of swimming studies the SL values are not normalised to swimmer's height and therefore the importance of height is overlooked. It is well documented that male swimmers have significantly higher V and longer SL compared to female ones across the front crawl events from 50-m to 400-m (Arellano et al., 1994; Kennedy et al., 1990; Pelayo et al., 1996; Seifert et al., 2007a), whereas no differences in SF were found between the sexes in any of those events (Pelayo et al., 1996). For instance, Pelayo et al. (1996) reported that in the 100-m front crawl events, male international-level swimmers displayed significantly higher V than the female (1.94 and 1.70 m·s$^{-1}$ respectively), by employing similar SF (51.37 and 49.37 cycles·min$^{-1}$ respectively) and achieving significantly longer SL (2.28 m and 2.07 m respectively). Thus, SL was the main contributor to the higher V of male swimmers due to greater body size and muscular strength of males (Pelayo et al.,
1996). Consequently, it can be clearly identified that male swimmers are able to achieve higher SL and V values than the female swimmers with similar SF.

2.2.3, Effect of skill level on V, SL and SF.

The skill level of the swimmers has been reported to differentiate V, SL and SF. Chollet et al. (1997) attempted to identify the differences in V, SL and SF between male swimmers of different skill levels. The participants were 402 physical education students who were assigned to six groups according to their performance in 100-m front crawl. The number (N) of participants of each group and their mean performance in 100-m front crawl were as follows: Group 1, N=80 and 96.14 s; Group 2, N=80 and 84.61 s; Group 3, N=82 and 77.99 s; Group 4, N=80 and 72.15 s; Group 5, N=80 and 65.14 s; Group 6, N=40 and 51.73 s respectively.

The researchers compared the 2 groups of more highly skilled swimmers (i.e. groups 5 and 6) and found that the most highly skilled swimmers of group 6 achieved significantly faster V values than group 5 swimmers (1.93 and 1.54 m·s⁻¹ respectively), longer SL (2.26 and 1.95 m respectively) and higher SF (51.6 and 47.8 cycles·min⁻¹ respectively) throughout the course of the 100-m race. Moreover, the researchers reported that the most highly skilled swimmers (group 6) displayed an ability to maintain these parameters more consistently between the two race laps compared to the swimmers of group 5.

Seifert et al. (2007a) investigated the effect of skill level on performance parameters during a 100-m front crawl at maximum effort. The researchers allocated the male participants of the study to three different groups (high-, medium- and low-skill) based on their personal best record in the 100-m front crawl. The performance level of those three groups, expressed as a percentage of the 100-m world record, was approximately 90%, 80% and 70% for the high-, medium- and low-skill group respectively. The investigators found that the high-skill group displayed significantly greater V and SL values compared to those of medium-skill and low-skill group. In addition, the high-skill group had significantly higher SF compared to the low-
skill group, whereas no significant differences were reported in SF between the high-skill and medium-skill groups. The V declined significantly during the last 25-m of the 100-m trial in relation to the first 25-m, corresponding to a decrease of 16.1% for the high-skill group, 18% for the medium-skill group and 23.8% for the low-skill group. Furthermore, the V of the high-skill group remained unchanged between the third 25-m and the fourth 25-m, while on the contrary, the V of the other 2 groups decreased significantly in the fourth 25-m in relation to the third one. SL for the high-skill group also remained stable throughout the four lengths, whereas it significantly decreased for the medium-skill and low-skill groups during the last two lengths corresponding to a decrease of 4% and 7.2% respectively.

From the findings of the above studies, it can be summarised that during the course of the 100-m front crawl race, the best swimmers are characterised by higher and more constant V, SL (Chollet et al., 1997; Seifert et al., 2007a) and SF (Chollet et al., 1997) values compared to the lower ability swimmers.

For front crawl swimming, Craig et al. (1985) reported that male finalists at U.S. Olympic trials in all the events from 100-m to 1500-m displayed lower SF and higher SL values compared to the swimmers that did not qualify for the finals. The researchers concluded that the finalists in all front crawl events could be distinguished from the others almost completely by their longer SL (Craig et al., 1985).

In summary, the effect of skill level on the kinematic parameters related to performance has not been adequately studied and methodological limitations do exist. Firstly, although there are data about races or race simulations, there is a lack of information regarding the discriminating factors between swimmers of different levels throughout training sets. Moreover, methodological limitations do exist in the above studies as explained in a following
section (2.2.5). Consequently, a comparison of elite and sub-elite swimmers during the course of a training set will add to the existing knowledge.

2.2.4. Effect of fatigue on V, SL and SF

The effect of fatigue on the performance parameters has been the point of interest for several studies. The impairment of swimming performance during races or testing protocols have been attributed to the reduced capacity of the swimmers to generate mechanical power under fatigued conditions (Toussaint et al., 2006).

Toussaint et al. (2006) found that the V and SF decreased significantly (12.4% and 10.6% respectively) between the first and the fourth 25-m lap during full-exertion arms-only 100-m front crawl, while the SL remained constant throughout the course of the race. The authors hypothesised that SF could be a scaling factor which apportions the propulsive forces to the reduction in power output with consequent lower speed, so that the SL remains more or less constant. Aujouannet et al. (2006) investigated the effect of fatigue on V, SL and SF during a testing protocol comprising of four 50-m maximal front crawl trials separated by 10 seconds. Comparing the first and the fourth trial, it was found that V and SF of international-level male swimmers decreased, while the SL remained constant. These findings are in line with those of Toussaint et al. (2006). Additionally, in accordance with the above findings, Chollet et al. (1997) and Suito et al. (2008) reported that V declined by 7% and 7.7% respectively during the second 50-m of 100-m front crawl race. The aforementioned researchers concluded that the development of exercise-induced fatigue during the maximal testing protocols accounted for the impairment in performance reflected by V reductions.

Contrary to the above findings in relation to SL, Alberty et al. (2005) reported that V and SL decreased by 12.5% and 7.9% respectively between the first and fourth 50-m lap of a maximal 200-m front crawl trial, while the swimmers did not manage to increase the SF to
counterbalance the shortening in SL. The authors stated that the reductions in SL were associated with the swimmers’ peripheral fatigue during the course of the trial. Furthermore, Alberty et al. (2009) examined the changes of SL and SF during even-paced front crawl swimming tests to exhaustion. Ten well-trained swimmers (8 males and 2 females) swam three times to exhaustion at three different speeds corresponding to 95%, 100% and 110% of their V at a pre-measured 400-m trial. The researchers found a progressive increase in SF along with a decrease in SL during all the three protocols. These results revealed that the swimmers maintained a constant V by increasing their SF with a concomitant shortening of their SL.

The discrepancy in the results of the above studies can be attributed to the large range of skill levels and genders of the swimmers that participated in those studies. Comparative data from testing swimmers of relatively equal skill level and of same sex would provide valuable information with respect to the effect of fatigue on those performance parameters.

Although the determination of V, SL and SF provides useful information about the swimming performance, the limitations of quantifying only these descriptive parameters is increasing (Alberty et al., 2005). This is due to the fact that the investigation of the aforementioned descriptive parameters does not provide any specific information about swimming technique (or changes in technique) or coordination (Seifert et al., 2004). This has led researchers to develop sophisticated methods and devices/equipment for the determination of other kinematic parameters, the measurement of those would provide advanced knowledge for better understanding of swimming technique and the associated changes in technique with fatigue.

### 2.2.5. Limitations of V, SL and SF calculations methods

Despite the fact that the aforementioned studies provided useful information about the performance parameters, several limitations exist, for example in the earlier studies, there have been different methods employed by the researchers for the determination of V, SL and SF.
The V was calculated either as the ratio between the whole distance swam and the time taken (Craig et al., 1985) or as the ratio between a certain distance in the midsection of the pool and the time spent for this specific distance (Arellano et al., 1994; Kennedy et al., 1990). Two methods were employed for the calculation of SL. According to the first method, researchers determined SL as the ratio between V and the average SF which was measured with the use of stopwatches (Craig et al., 1985), while according to the second method, the SL was calculated as the V divided by the average SF with the data collected in the midsection of the pool and analysed with computer-based digitising methods (Arellano et al., 1994; Kennedy et al., 1990). SF was calculated as the average SF for a number of stroke cycles in the midsection of the pool using stopwatches (Craig et al., 1985) or digitising methods (Arellano et al., 1994; Kennedy et al., 1990). The aforementioned techniques for the calculation of V, SL and SF were based on total time of the race and/or lap times of the race, meaning that the effect of start and turn phases was not considered. It is well documented, that swimmers achieve their highest V at start and turn phases (Thompson et al., 2000) and therefore those non-swimming elements should be excluded from the calculations of those performance parameters. Since V, SL and SF were determined differently among the aforementioned studies and no reliability tests and/or correcting factors have been suggested, the use of methodological approaches and their reliability should be taken into consideration for the interpretation and comparisons of the findings. This statement is supported by Chollet and Pelayo (1999) who suggested that different methodological procedures in the calculation of the SL result in errors and discrepant results.

More recently, V, SL and SF have been assessed based on more accurate methods with the use of video analysis. V, SL and SF were calculated using the video images of swimmers in the mid-section (10-22.5 m marks) of the pool in front crawl (Chollet et al., 2000; Seifert et al., 2004) and in the other strokes (Chollet et al., 2004; Chollet et al., 2006; Chollet et al., 2008; Seifert and Chollet 2005). In these studies, SL and SF were calculated based on the V of a
fixed point (typically the hip) rather than on the centre of mass (COM) of the swimmers. It has been reported that the use of a fixed point does not represent most kinematical variables of the COM (Fernades et al., 2012; Figueiredo et al., 2009; Psyrcharakis and Sanders, 2009). For instance, Psyrcharakis and Sanders (2009) reported that the use of hip marker overestimates the maximum and underestimates the minimum instantaneous velocity within a stroke cycle.

In recent studies, V, SL and SF were quantified with the use of three-dimensional (3D) motion analysis (Figueiredo et al., 2013a; 2013b; McCabe et al., 2011; Psyrcharakis et al., 2010). In those studies, the kinematic variables were calculated based on the COM data. This technique requires precise anthropometric data and it is universally accepted that the COM profile accurately reflects the swimmer’s motions, as intersegment actions affect the kinematics when a fixed body landmark is used as a reference point.

To summarise, the most accurate method of calculating V, SL and SF is with the use of 3D motion analysis of the COM. However, the changes in the performance variables during intermittent maximal swimming exercise have not been adequately studied, especially during training sets longer than 200-m which are commonly used by coaches. Such data, will allow coaches to develop training programs and strategies in order to limit the decreases in performance parameters.

2.3. Kinematic variables associated with swimming performance

2.3.1. Stroke index

Costill et al. (1985) introduced the concept of stroke index (SI) which has been linked to swimming performance. SI is defined as the product of SL and V (expressed in m²-cycles⁻¹).
and has been suggested as a tool to assess swimming ability (Pelayo et al., 1997) and as a measure of successful performance (Costill et al., 1985; Sánchez and Arellano, 2002).

Male swimmers have been found to produce higher SI values than their female counterparts in all the events (Sánchez and Arellano, 2002). Also, front crawl appears to have the greatest SI value compared to the other competitive swimming strokes, as in 100-m races of elite male swimmers, SI was 4.03 m²-cycles⁻¹-min⁻¹ in front crawl, 3.57 m²-cycles⁻¹-min⁻¹ in back crawl, 3.36 m²-cycles⁻¹-min⁻¹ in butterfly and 2.53 m²-cycles⁻¹-min⁻¹ in breaststroke (Sánchez and Arellano, 2002). Furthermore, SI has been found to be significantly related to the performance in 400-m front crawl (Jürimäe et al., 2007). The association between SI and performance has been found in all competitive swimming strokes/distances (Sánchez and Arellano, 2002) and it is suggested that SI can be used as an index of propulsion efficiency (Longo et al., 2008).

The aforementioned studies provided valuable data with respect to the use of SI as a tool of assessing swimming performance. However, limitations in the calculation of SI do exist, as V was determined in the whole distance swum without taking into consideration the non-swimming elements (Longo et al., 2008) or V was calculated based on the head marker in the midsection of the pool (Jürimäe et al., 2007; Sánchez and Arellano, 2002).

2.3.1.1. Effect of skill level on SI

Sánchez and Arellano (2002) compared elite swimmers (males and females who participated in preliminaries and finals at World short course championships) with sub-elite swimmers (male and female competitors in in preliminaries and finals at Spanish winter championships). The researchers reported that during competition, elite swimmers displayed greater SI values than sub-elite swimmers across all four strokes and distances. According to the results of the aforementioned study, in 100-m front crawl event, elite swimmers displayed SI of 4.03 m²-cycles⁻¹-min⁻¹, whereas sub-elite swimmers achieved SI of 3.86 m²-cycles⁻¹-min⁻¹,
corresponding to a difference of 4.4% between elite and sub-elite. Seifert et al. (2010a) examined the effect of skill level on SI during incremental 25-m trials (60-100% of maximum speed). These researchers, in line with the results of Sánchez and Arellano (2002), found that elite swimmers were characterised by larger SI throughout the increments of the test. Complementarily, Mason and Cossor (2000) reported significant correlations between performance and SI (r=0.61) in male swimmers in 50-m and 100-m front crawl events. It is evident that the effect of skill level on swimming efficiency (as expressed by SI) has not been adequately studied during maximal training sets. This type of data, will orient coaches with respect to the design of training programs with focus on technical enhancement.

2.3.1.2. Effect of fatigue on SI

Longo et al. (2008) examined the effect of fatigue on SI during a maximal 400-m front crawl trial in young swimmers (boys and girls under 18 years of age). The researchers reported significant decreases in SI for both boys (24.1%) and girls (20.0%) between the first and the fourth 100-m section of the trial. Komar et al. (2012) reported that the SI of elite sprint swimmers remained unchanged during 6 incremental 300-m trials in front crawl.

Although the vast majority of the studies conducted in swimming biomechanics have reported V and SL values (components of SI), SI has not been adequately reported. There is lack of data with respect to changes in the efficiency due to fatigue, especially during intermittent maximal exercises in which the anaerobic metabolism dominates over the aerobic metabolism. Indeed, Komar et al. (2012) and Longo et al. (2008) speculated that the testing protocols which were employed in their studies (i.e. incremental test and 400-m maximal trial) imposed aerobic paces that sprint swimmers are not usually train at. Thus, efficiency data of sprint swimmers during maximal sets that the anaerobic contribution dominates would be of great interest for the coaches in order to design more effective training programs.

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2.3.1.3. Limitations of studies on SI

The results of the aforementioned studies should be interpreted cautiously as limitations exist. For instance, with respect to the study of Longo et al. (2008), two limitations have been identified. Firstly, for the calculation of SI, the total time of the trial (including dive start and turns) was used and secondly, the calibre of the swimmers participated in the study was not reported. Furthermore, in the study of Sánchez and Arellano (2002), the comparisons between elite and sub-elite swimmers with respect to SI was based only on a single measurement at the first stage/length of each race, meaning that possible differences between skill levels at later stages of the race were not assessed. Finally, the use of a fixed body landmark was used for the calculation of V (Komar et al., 2012) which is a source of error as discussed previously (section 2.2.5).

2.3.2. Duration of stroke phases

According to Sanders (2002), swimmers can increase their propulsive impulse by increasing the time, relative to the duration of the stroke cycle, over which propulsive forces are applied. Thus, it is necessary to define the propulsive and non-propulsive phases of a stroke cycle in front crawl and investigate the research findings in relation to the phase durations.

2.3.2.1. Definition of stroke phases in front crawl

The stroke cycle in front crawl has been divided in several different ways (2D or 3D) depending on the researchers’ purpose. With respect to 2D approaches, Holmér (1974) and Richardson et al. (1979) simply divided the stroke cycle into two phases: work phase (underwater) and recovery phase (above water). The former study examined the energy cost of swimming with arms only and legs only, while the latter investigated the risk of shoulder injury during phases. More recently, Chollet et al. (2000) defined the stoke phases in front crawl as:
- Entry and catch phase, from the time the hand enters the water to the beginning of the hand’s backwards movement.

- Pull phase, from the time the hand starts moving backwards to the time the hand is vertically aligned with the shoulder.

- Push phase, from the time the hand is in vertical alignment with the shoulder to the time the hand exits the water.

- Recovery phase, from the time from hand’s exit from the water to its following entry into the water.

The definition of Chollet et al. (2000) has been adopted by many researchers (Figueiredo et al., 2013b; Komar et al., 2012; McCabe et al., 2011; McCabe and Sanders, 2012; Seifert et al., 2004; 2005; 2007a; 2007b; 2010a; 2010b). The aforementioned pull and push phases as defined by Chollet et al. (2000) constitute the propulsive phases of the arms, whereas the entry/catch and recovery phases are regarded as the non-propulsive phases.

Although the use of 2D definition served the purpose of the above studies, researchers have adopted more complex 3D definitions by dividing the underwater part of the stroke cycle into more phases in order to reflect the underwater path in all three directions. Hay (1993) divided the underwater phase as the downsweep, insweep and upsweep, while Costill et al. (1992) and Maglischo (2003) divided the whole stroke cycle in 5 phases: entry-stretch; downsweep-catch; insweep; upsweep and release.

In front crawl, the arms contribute most significantly (approximately 85%) to the propulsion, whereas the contribution of the legs is limited (Deschodt et al., 1999). Thus, the duration of the phases over which the arms produce (or do not produce) propulsion, and the arm coordination with respect to the continuity of application of propulsive forces, have been the
point of interest for several studies (Chollet et al., 2000; Komar et al., 2012; Seifert et al. 2004; 2005; 2007a; 2007b; 2010a; 2010b).

The absolute and relative (expressed as percentile of the stroke cycle) durations of the stroke phases have been linked with the performance parameters (Chollet et al., 2000; Hay, 1993; Keskinen and Komi, 1993). For instance, Chollet et al. (2000) reported that in front crawl, as V increased from a pace corresponding to 800-m race to a pace of 50-m race, the relative duration of the pull and push phases increased concomitant with a decrease in the relative duration of the catch phase.

2.3.2.2. Effect of skill level on phase durations

The relative durations of propulsive and non-propulsive phases have been used as a tool to discriminate skill level. Chollet et al. (2000) reported that, as V increased, highly skilled swimmers managed to decrease the relative duration of the non-propulsive phases and lengthened the relative duration of propulsive phases to a greater extent compared to less skilled swimmers. This indicates that highly skilled swimmers are able to modify their technique during a given task. In general agreement with the aforementioned results, Seifert et al. (2010a) reported that national-level swimmers displayed longer relative duration in push phase and shorter in entry phase compared to regional-level swimmers (incremental 25-m trials). During a 100-m race simulation, Seifert et al. (2007a) reported that highly skilled swimmers were characterised by a longer relative duration of the propulsive phases (54% of the duration of the stroke cycle).

The effect of skill level on phase durations during a maximal intermittent training set is still to be investigated. The examination of this matter will provide coaches with data regarding the differences in the temporal characteristics of the arm actions during the stroke cycle and potentially reveal differences that discriminate the skill levels.
2.3.2.3. Effect of fatigue on phase durations

Alberty et al. (2005) reported that the development of fatigue during a maximal 200-m trial in front crawl resulted in a significant increase in the relative duration of the propulsive phase from 38.2% in the first 50-m lap to 42.3% in the last 50-m lap, concomitant with a decrease in the non-propulsive phase from 61.8% to 57.7% respectively. The same temporal adjustments were reported by Alberty et al. (2008) during continuous maximal effort to exhaustion at a constant speed. Alberty et al. (2008) stated that increases in SF at the last stage of the trial resulted in changes of the temporal characteristics of the stroke, as decreases in the non-propulsive phase and particularly in the entry phase were observed. The latter finding is in opposition to the results of Aujouannet et al. (2006) who reported an increase in the relative duration of the entry phase during 4 maximal 50-m trials. Bassan et al. (2016) examined the effect of fatigue on stroke phase durations during continuous maximal trial to exhaustion at a speed corresponding to 400-m race pace. The researchers observed significant increases in relative durations of pull (from 26.5% to 33.3%) and push (from 21.1% to 24.9%) phases accompanied by decreases in entry (from 27.2% to 20.8%) and recovery (from 25.0% to 20.1%) phases between the beginning and the end of the trial respectively. The results of Bassan et al. (2016) confirmed the findings of Alberty et al. (2005; 2008), however, in contrast to these findings, Seifert et al. (2007a) observed a decline in the relative duration of the propulsive phase of elite male swimmers between the first and last 25-m lap of a 100-m race. This discrepancy in the finding may be attributed to the different skill levels of the swimmers tested and/or the different testing protocols.

From the aforementioned studies, it can be summarised that the development of fatigue seems to cause an increase in the relative duration of the propulsive phase. This increase in the duration over which the arms apply propulsive forces is not necessarily translated into propulsion of the whole body. This is due to the fact that, apart from the duration, the propulsive forces depend upon several other factors, such as hand direction, hand path, hand
velocity and angle of the hand during the pull and push phases and anthropometry (Seifert et al., 2004; Toussaint and Beek, 1992).

2.3.2.4. Limitations of studies on stroke phase durations

The main limitation of the aforementioned studies is related to the definition of the propulsive phases and particularly the push phase. As the hand approaches the thigh (last part of the push phase) it stops pressing the water backwards and starts moving forward (Maglischo, 2003). Thus, the last part of the push phase, as defined by Chollet et al. (2000), is considered non-propulsive. Indeed, McCabe et al. (2011) and McCabe and Sanders (2012) modified the aforementioned definition by defining the end of backward movement of the hand as the end of the push phase and therefore the end of the application of propulsive forces. Another limitation is that the studies in which continuous maximal trials at constant speed were employed, the stroke phase durations were assessed only at the beginning and at the end of the trial, which means that there is lack of data regarding the changes in temporal characteristics as fatigue develops.

2.3.3. Shoulder and hip roll

In front crawl and backstroke, the alternation between right and left arm strokes is accompanied by angular motion of the trunk (shoulders and hips) around its longitudinal axis commonly known as body roll (Psycharakis and Sanders, 2010). This angular motion of the trunk has been linked with swimming performance in front crawl (Castro et al., 2003; Payton et al., 1999; Psycharakis and Sanders, 2010) by increasing propulsion or decreasing resistive forces (Castro et al., 2003; Maglischo, 2003), facilitating the breathing action (Hay et al., 1993), bringing the large muscles of the trunk into play for greater force production (Colwin, 1977; Maglischo 2003) and reducing the possibility of shoulder injury (Tovin, 2006). Thus, it is important to investigate possible changes in body roll over the course of maximal
intermittent swimming exercise and also to compare swimmers of different skill level with respect to body roll angles.

Investigators have examined the effect of body roll on front crawl swimming kinematics by considering that the body rolls as a rigid segment (Hay et al., 1993; Liu et al., 1993; Payton et al., 1997; Payton et al., 2002) or by analysing the shoulder and hip roll separately (Cappaert et al., 1995; Figueiredo et al., 2013b; McCabe and Sanders, 2012; McCabe et al., 2011; 2015; Psycharakis and Sanders, 2008; Sanders and Psycharakis, 2009; Yanai, 2003). Although the former studies provided useful data with respect to body roll, Cappaert et al. (1995) showed that shoulders and hips roll independently both in terms of magnitude and temporal characteristics. Thus, the assumption that the body rolls as a rigid segment is not tenable.

From studies in which the assumption that body rolls as a rigid segment was adopted, it has been suggested that the body roll affects the propulsive forces produced by the upper limbs. Hay et al. (1993) and Payton et al. (1997) conducted simulation studies whereas Liu et al. (1993) conducted experimental study in order to examine the effect of body roll on the underwater kinematics of the hand. The conclusion from those studies was that, in front crawl, the body roll influences the displacement and speed of the hand in the mediolateral direction (perpendicular to swimming direction), and therefore it possibly affects the propulsive forces produced by the hand. However, Payton et al. (2002) challenged the findings of the aforementioned studies and reported no contribution of the body roll on hand displacement and speed. Clarys and Jiskoot (1974) highlighted that the body roll contributed to the decrease of resistive forces by reducing the frontal surface area. Lecrivain et al. (2010), with the use of computational fluid dynamics, found a positive relationship between the body roll angle and the propulsive forces produced by the upper arm.
Castro et al. (2003) stated that one of the important functions of the body roll is to prevent the undesirable lateral movements of the body during swimming. In their study, Castro et al. (2003) measured the body roll angles of male sprint specialists in front crawl at three different swimming velocities (warm up pace; 1500-m pace; 50-m pace) and two conditions: a) whilst breathing to the preferred side every stroke cycle and b) no breathing. It was found that, as the swimming speed increased from 1.27 m·s⁻¹ to 1.88 m·s⁻¹ and from 1.33 m·s⁻¹ to 1.94 m·s⁻¹ in breathing and non-breathing condition respectively, the body roll angle decreased from 139 degrees to 113 degrees and from 129 degrees to 110 degrees respectively. Castro et al. (2003) also stated that if swimmers could increase or maintain their body roll when swimming faster, this could possibly decrease the resistive forces that a swimmer obtains in the water. Additionally, Castro et al. (2006) found negative relationship between the body roll angle and SF.

On the other hand, 3D analysis methods were employed for the quantification of shoulder and hip roll separately (Cappaert et al., 1995; Figueiredo et al., 2013b; McCabe and Sanders 2012; McCabe et al., 2011; 2015; Psycharakis and Sanders, 2008; Sanders and Psycharakis 2009; Yanai, 2001; 2003).

Yanai (2001) reported mean angle values of 58 degrees and 36 degrees for shoulder and hip roll respectively whilst swimming at a V of 1.6 m·s⁻¹. In a subsequent study, Yanai (2003) found that the shoulder roll angle decreased by 9 degrees (from 75 to 66 degrees) when V increased from 1.3 to 1.6 m·s⁻¹. Psycharakis and Sanders (2008) with the use of 3D methods quantified the body roll of 10 male national- and international-level swimmers during the course of a 200-m front crawl at maximal intensity. The researchers, in agreement with Yanai (2001), found that the swimmers rolled their shoulders significantly more than their hips, reporting average values of 53 degrees and 25 degrees respectively. Similar findings with respect to the roll magnitudes were reported by McCabe et al. (2011) and McCabe and Sanders
(2012), who examined the shoulder and hip roll angles of sprint and distance swimmers in two conditions: a) when swimming at sprint pace and b) when swimming at distance pace. At a sprint pace, the sprint swimmers displayed total (sum of right and left sides) shoulder roll angles of 106 degrees and hip roll angles of 36 degrees at a V of 1.81 m·s⁻¹, while the distance swimmers displayed shoulder and hip roll angles of 106 degrees and 40 degrees respectively while swimming at 1.80 m·s⁻¹. At distance pace (V=1.41 m·s⁻¹ and V=1.50 m·s⁻¹ for sprint and distance swimmers respectively), both sprint and distance swimmers displayed total shoulder roll angles of 111 degrees, while the total hip roll angles were found to be 57 and 51 degrees respectively. The researchers stated that the total shoulder and hip roll angles between sprint and distance swimmers were not significantly different when swimming at sprint or distance pace. Finally, with respect to the effect of lower limbs action on the body roll, Sanders and Psycharakis (2009) suggested that the leg action is likely to limit the rotation of the hips.

2.3.3.1. Effect of skill level on shoulder and hip roll

Cappaert et al. (1995) using 3D methods quantified the shoulder and hip roll of 12 male swimmers of different skill level (5 elite and 7 sub-elite) during the 100-m front crawl event at the 1992 Olympic Games. The researchers reported significantly greater shoulder roll angle values compared to those of the hips for both elite and sub-elite group. The former group displayed mean shoulder and hip roll values of 35.4 degrees and 8.3 degrees respectively whilst swimming at a V of 2.01 m·s⁻¹, while the latter at a V of 1.87 m·s⁻¹ demonstrated 34.4 degrees and -17.8 degrees (i.e. the negative roll angles indicate that shoulders and hips were rolling in opposite directions) for shoulder and hip roll angles respectively. The latter finding suggests that the sub-elite swimmers displayed a non-symmetrical body roll pattern, while on the contrary, the elite swimmers displayed a symmetrical body roll pattern with shoulders and hips rolling to the same direction. It was further suggested that the non-symmetrical body roll pattern of the sub-elite swimmers possibly increased the resistive forces (increase in frontal surface area) obtained in the water, whereas in the case of elite swimmers the resistive forces
were reduced due to a symmetrical body roll. These findings of Cappaert et al. (1995) were in general agreement with those of Yanai (2001; 2003) with respect to the magnitude of shoulder roll being considerably greater compared to the one of the hip roll. However, there was some conflict in the findings of those studies with respect to the changes in roll magnitude with V. On the one hand, Cappaert et al. (1995) reported no difference in swimmers’ shoulder roll angles for different V, while on the other hand, Yanai (2003) reported a decrease in shoulder roll angles when V increased. Psycharakis and Sanders (2008), in agreement with Yanai (2003), reported a significant negative correlation between the shoulder roll angles with V during a maximal 200-m trial, which indicates that the faster swimmers were rolling their shoulders less than the slower swimmers. This discrepancy in the results may be attributed to the different skill level of the participants in those studies and/or to the different velocities tested. Furthermore, the effect of breathing actions on the magnitude of the body roll was not taken into account by Yanai (2003) nor Cappaert et al. (1995). Indeed, it has been reported that swimmers rolled their shoulders 9 degrees more during breathing conditions compared to non-breathing conditions (Payton et al., 1999). This finding was further supported by McCabe et al. (2015) who found 12 degrees greater shoulder roll angles in the recovery phase of the arm when breathing compared to non-breathing.

To date, only Cappaert et al. (1995) examined the effect of skill level on shoulder and hip roll in competition environment. However, no relative data exists regarding the influence of skill level on the roll magnitudes during a maximal set in a training environment. This data will advance the knowledge of the coaches with respect to roll strategies adopted by swimmers of different skill level as a function of intensity and task.

2.3.3.2. Effect of fatigue on shoulder and hip roll

Psycharakis and Sanders (2008) found that, during the course of a maximal 200-m trial and as V decreased as a consequence of fatigue, the swimmers increased their hip roll and while they
maintained constant shoulder roll. Contrary to the findings of Psycharakis and Sanders (2008), Figueiredo et al. (2013b) reported a significant increase in shoulder roll angle in the third 50-m lap in relation to the first lap (from 107 to 118 degrees) of a maximal 200-m trial.

It is evident that the effect of fatigue on the body roll magnitudes has not been adequately investigated especially during a maximal training set. Considering that body roll has been linked in several ways with swimming performance, adaptations in roll magnitudes imposed by fatigue will advance the knowledge in this field and will provide data that can be used by coaches in the context of feedback orientation.

2.3.3.3. Limitations of studies on shoulder and hip roll

As mentioned earlier, the assumption that body rolls as a rigid segment during front crawl constitutes a major limitation, as it is now well established that shoulders and hips roll independently (Cappaert et al., 1995; Psycharakis and Sanders, 2008). Therefore, the shoulder and hip roll should be examined separately.

Moreover, limitations exist with respect to simulation studies in which the body roll was investigated, as the validity of the models used for the assessment of body roll was not established. Indeed, Payton et al. (2002) stated that some of the assumptions in the simulation studies were incorrect. For example, the researchers in the simulation studies assumed incorrectly that the trunk rolls counter-clockwise from the neutral position (Payton et al., 2002).

Finally, another source of error is that the investigators did not take into consideration the effect of breathing actions for the assessment of the body roll, as it is evident that the breathing actions alter the magnitude of body roll (McCabe et al., 2015; Payton et al., 1999).
On the basis of the above limitations, it has been suggested that the most accurate method for the assessment of shoulder and hip roll is with use of 3D techniques whilst breathing actions are controlled (Pscharakis and Sanders, 2008).

### 2.3.4. Intracycle Velocity Variations

An important implication of the duration of propulsive and non-propulsive phases is associated with the investigation of the V within a stroke cycle. It is well established that periods of acceleration and deceleration do exist within each stroke cycle in all four competitive strokes (Barbosa et al., 2008; Maglischo et al., 1989), and thus V is not constant during the stroke cycle. Since acceleration of the swimmer’s body indicates that propulsive forces are greater than the resistive ones and deceleration indicates the opposite (Colman et al., 1998), it has been suggested that the V fluctuations within a stroke cycle represent the balance between propulsive and resistive forces (Barbosa et al., 2013). Intracycle velocity variations (IVV) have been defined as the fluctuations of the instantaneous swimming velocity during a stroke cycle as a result of the application of propulsive and resistive forces acting on the swimmer’s body (Miller, 1975) and have been linked with swimming performance (Takagi et al., 2004).

Several methods have been used for the calculation of IVV. The two methods that have been widely employed by the researchers are: a) the IVV is calculated as the difference between the maximum and minimum instantaneous value of V (Pscharakis and Sanders, 2009; Pscharakis et al., 2010) or b) the IVV is determined by the quantification of the coefficient of variation, being expressed as a percentage according to the following equation (Barbosa et al., 2005; Figueiredo et al., 2012a; Schnitzler et al., 2010):

\[ IVV = \left( \frac{\text{standard deviation of velocity}}{\text{mean velocity}} \right) \times 100 \]

The kinematic parameters in relation to IVV include the amplitude of IVV, the maximum instantaneous velocity (Vmax), the minimum instantaneous velocity (Vmin) and their
respective relative values IVV%, Vmax% and Vmin% expressed as percentile of the average horizontal V (Vmeanx) of the stroke cycle (Pscharakis et al., 2010). In this section, research conducted in relation to IVV is summarised.

To date, a number of methods have been developed and improved for the assessment of IVV. According to Vilas-Boas et al. (2011), those methods can be categorised into two categories: a) a fixed body landmark evaluation (usually the hip), and b) the swimmer’s overall COM evaluation. The studies assigned to the first category employed 2D videography analysis (D’Acquisto and Costill, 1998; Maglischo et al., 1989; Takagi et al., 2004) or developed mechanical devices such as speed-meters which were attached on the swimmers’ waists through a cable (Albery et al., 2005; Barbosa et al., 2013; Leblanc et al., 2007). Alternatively, the studies of the second category employed 3D videography to assess IVV of the whole COM (Cappaert et al., 1995; de Jesus et al., 2015; Figueiredo et al., 2012a; 2013a; Pscharakis et al., 2010; McCabe et al. 2011; McCabe and Sanders, 2012). In section 2.3.4.4 the methods for the estimation of body’s COM are summarised. It should be noted, that the studies which employed 3D motion analysis for the assessment of IVV, reported values in all three directions (horizontal, vertical, lateral).

Maglischo et al. (1989) tested elite male and female swimmers’ IVV at maximum intensity in front crawl. Marked periods of acceleration and deceleration were identified within the stroke cycle as the participants in the study displayed two distinct peaks in the V patterns. Maglischo et al. (1989) also stated that the measurement of IVV indicates when and to what extent certain phases of the stroke cycle are propulsive and provides also important information about models of propulsive efficiency. In this sense, it has been suggested that IVV can be used as a measure of swimming efficiency, as, at least theoretically, reduction in velocity fluctuations reduces swimmers’ energy expenditure and vice versa (Vilas-Boas et al., 2011).
2.3.4.1. Effect of skill level on IVV

Togashi and Nomura (1992) investigated the magnitude of IVV of 25 novice swimmers in butterfly with the use of 2D methods. The researchers reported a significant negative relationship (r=-0.51) between the IVV in the swimming direction (horizontal) and V in two 25-m trials at maximum effort. In other words, swimmers who achieved higher V values had smaller fluctuations in their horizontal velocity in comparison to the slower swimmers. However, the fact that the participants in this study were novice swimmers, restricts the generalisation of the findings in the context of elite swimming. D’Acquisto and Costill (1998), using 2D methods, examined the IVV in well-trained male and female breaststroke specialists. The researchers found that the most skilled swimmers achieved higher Vmax and managed to minimise the drop in their V (i.e. higher Vmin) in a sprint bout (22.86 m). Takagi et al. (2004) examined the hip IVV of male and female swimmers in 50-m, 100-m and 200-m races during the FINA World Championships in Fukuoka (2001). The researchers, in order to investigate the effect of performance level on IVV, assigned the swimmers into two groups. The first group was comprised of sub-elite swimmers who were eliminated at the heats, while the second was comprised of elite swimmers who managed to qualify for the semi-finals and finals. The results showed that the sub-elite group displayed significantly higher relative IVV values compared to the elite group across the three studied events. Further, the elite swimmers displayed higher relative Vmin during the stroke cycle compared to the sub-elite swimmers. The researchers concluded that the higher relative IVV of the sub-elite group was a result of a very low relative Vmin and not from the Vmax achieved within the stroke cycle. However, Leblanc et al. (2007), based on the data collected from a speed-meter, stated that elite swimmers demonstrated greater variations in their hip Vmeanx compared to sub-elite swimmers at three different paces corresponding to 200-m, 100-m and 50-m race pace. Schnitzler et al. (2010) examined the IVV of the hip in front crawl with the use of speed-meter over 4 swim trials at different intensities/speeds (60-100% of maximal speed). The 22 male participants in this study were assigned to either an elite (national and international level
competitors; average personal best time in 100-m front crawl 50.54 seconds) or recreational (non-competitive swimmers; average personal best time in 100-m front crawl 74.75 seconds) group. The investigators found that the elite swimmers were characterized by lower relative IVV over the 4 trials compared to the recreational swimmers, as the average relative IVV values over the trials were 14.4% and 17.8% for the elite and recreational group respectively. Using the same method with Schnitzler et al. (2010), Seifert et al. (2010a) assessed the IVV of the hip of national-level and regional-level front crawl specialists during 8 trials of 25-m from slow (approximately 60% of maximum) to maximal speed. The relative IVV for each group did not change significantly over the course of the trials and also no difference in relative IVV was found between elite-level and regional-level swimmers over the trials. This latter finding is in contrast with the findings of Schnitzler et al. (2010). This discrepancy in the results between the studies of Schnitzler et al. (2010) and Seifert et al. (2010a) may be attributed to the fact that, in the former study, recreational swimmers were compared to elite swimmers, whereas in the latter study, competitive swimmers of different calibre were compared.

In summary, the effect of skill level on IVV has not been adequately studied in front crawl and the results of the existing literature are discrepant. Furthermore, no studies have assessed the effect of skill level on IVV with the use of 3D motion analysis of the COM. This method has been suggested to be the most accurate one in analysing IVV (Figueiredo et al., 2009; Psycharakis and Sanders, 2009; Psycharakis et al., 2010). The methodological limitations of the studies with respect to IVV are summarised in a later section (2.3.4.3).

2.3.4.2. Effect of fatigue on IVV

Alberty et al. (2005) used a speed-meter to examine the effect of fatigue on hip IVV in front crawl. Seventeen competitive swimmers (13 males and 4 females) performed two 25-m trials of maximum effort, before (rested condition) and immediately after (fatigued condition) a
maximal 200-m bout. The investigators reported no significant changes were observed in relative horizontal IVV between rested and fatigued conditions. The researchers reported relative Vmax and Vmin values to be approximately 124% and 79% respectively of Vmeanx.

Psycharakis et al. (2010) employed 3D analysis methods to investigate the IVV of elite swimmers in all three directions (x, y, z) over the course of a maximal 200-m trial. Four stroke cycles were analysed, one in each one of the 4 laps of the trial. Although the researchers reported a significant decrease in Vmeanx as the trial progressed as a result of fatigue, no significant changes in any of the 3 directions were reported in absolute or relative IVV during the trial. The absolute Vmax and Vmin in the swimming direction (x) were found to be significantly higher in lap 1 compared to the other 3 laps, while the relative Vmax and Vmin values in the same direction remained remarkably similar throughout the trial. The average relative horizontal Vmax and Vmin of the 4 laps were found to be 111% and 89% respectively. Finally, the researchers stated that the IVV in vertical and lateral directions were greater in magnitude compared to horizontal IVV. However, the vertical and lateral IVV values were not correlated with Vmeanx. Nevertheless, the researchers suggested that further research needs to be conducted on the causes and effects of IVV magnitudes in lateral and vertical directions. Figueiredo et al. (2012a) also employed 3D analysis methods to investigate the IVV of 10 high-level male swimmers during a maximal 200-m trial in front crawl. In agreement with the results of Psycharakis et al. (2010), the researchers found that Vmeanx decreased and relative IVV remained constant (in all three axes) throughout the course of the trial. The same authors reported on average higher relative Vmax and lower relative Vmin values (approximately 125% and 75% respectively) in comparison to those reported by Psycharakis et al. (2010). Another study that the effect of fatigue on IVV was studied with the use of 3D methods was the one of de Jesus et al. (2015). Ten male swimmers performed 7 incremental 200-m trials in front crawl until exhaustion. No significant changes in relative IVV in the swimming direction were found either within or between the increments. These results suggest
that the relative IVV was not affected by the increasing Vmeanx or the increasing fatigue and are in line with the results of Psycharakis et al. (2010) and Figueiredo et al. (2012a).

Considering the existing literature on IVV, it can be clearly seen that no studies have examined the effect of fatigue on IVV during an intermittent maximal training set longer than 200-m. Since such training sets are commonly used in daily practice, the investigation of the adjustments in technique imposed by fatigue and the possible differences in those adjustments in relation to skill level will advance the knowledge in this field.

2.3.4.3. Limitations of the studies on IVV in front crawl

Although the aforementioned studies have provided useful data with respect to IVV, methodological limitations do exist. Several studies examined IVV hypothesising that the hip satisfactorily represents the kinematics of the COM. However, it has been reported the hip does not accurately represent the COM (Figueiredo et al., 2009; Psycharakis and Sanders, 2009). Indeed, Psycharakis and Sanders (2009) stated that using the hip as a referenced marker, Vmax of COM is significantly overestimated, whereas Vmin and IVV are significantly underestimated (p≤0.001). Furthermore, Fernandes et al. (2012) stated that the error in IVV results obtained from the hip point should be taken into consideration in data interpretation. These errors in the calculations have been attributed to the fact that the hip joint is also dependent on an individual’s differing trunk rotations, and inertial effects created by forward or backward leg or arm movements, even when no propulsion or resistance is generated (Colman et al., 1998).

Another source of error could be the assumption of bilateral symmetry by some researchers who employed 2D analysis methods for the investigation of IVV (Psycharakis and Sanders, 2009). Additionally, due to the body roll in front crawl, the hips move in opposite directions in the vertical and lateral axes of motion. As a matter of fact, the use of hip velocity as an
indication of the velocity of the COM can be only used in the horizontal direction (Psycharakis and Sanders, 2009).

2.3.4.4. Calculation of COM in swimming motion analysis

To date, several studies have assessed kinematic variables in swimming based on the COM profile of the swimmer. For an accurate calculation of the kinematic variables especially with the use of 3D motion analysis, various anthropometric data are required. These anthropometric data include the volume, mass and COM of body segments as well as of the whole body. Different methods have been used to locate swimmers’ COM. The anthropometric data have been obtained with the use of different methods. The most important methods developed in this area are presented in this section.

2.3.4.4.1. Data from cadavers

Initially, anthropometric data were obtained from cadavers through dissection techniques (Chandler, 1975; Dempster, 1955; Liu et al., 1971). Dempster (1955) obtained anthropometric data from cadavers' body segments. In this study, the mass of each segment was determined with the use of a balance plate, while the volume of each segment was calculated with the employment of immersion technique. A free swinging pendulum system was used for the quantification of each segment's moment of inertia. Dempster’s anthropometric data has been widely used in swimming research (Cappaert et al., 1995; Maglischo et al., 1987; Nikodelis et al., 2005; Sanders et al., 1992; 1995). Maglischo et al. (1987) employed Dempster’s method to assess the relationship between the velocity of the hip and the velocity of the COM in all four competitive strokes. It was concluded that the velocity of the hip does not accurately reflect the actual swimming velocity of the swimmer. For example, in breaststroke swimming with the hip as a referenced marker, the Vmax was overestimated and the Vmin underestimated. The researchers concluded that the COM should be used in kinematic analyses to eliminate the errors. However, limitations with data obtained from cadavers have been
identified. The major limitation in cadaver studies is that those studies conducted on small samples of limited populations (elderly white Caucasian males), and therefore the implementation of the results to different samples (such as athletes) is questionable. Furthermore, according to Zatsiorsky (2002) another source of error derives from the different tissue densities between cadavers and living subjects, which causes errors in the calculation of segmental moments of inertia.

2.3.4.4.2. Regression equations

Another method used to estimate the inertial parameters of the human body was the development of regression equations. Clauser et al. (1969) examined 13 Caucasian male cadavers (average age 49.3 years) and developed regression equations for the estimation of the segmental parameters based on anthropometric measurements such as depth, length and circumference of each segment. Zatsiorsky and Seluyanov (1983; 1985) developed more than 150 regression equations to quantify the segmental parameters. In these studies, the mass, COM locations and moments of inertia of the body segments were calculated with the use of a gamma-mass scanner and derived regression equations. Although the latter technique seems to produce accurate segmental data, de Leva (1996) highlighted that the calculations of segments’ length by Zatsiorsky and Seluyanov (1983; 1985) reduces the accuracy of locating segments’ COM due to the fact that bony landmarks instead of centre of joints were used. Based on the aforementioned source of error, de Leva (1996) adjusted the COM calculations suggested by Zatsiorsky and Seluyanov (1983; 1985). The calculations of the COM developed by de Leva (1996) have been used by several researchers in swimming motion analysis (Barbosa et al., 2005; 2006; 2008; de Jesus et al., 2015; Figueiredo et al., 2009; 2012a; 2012b; 2013a; 2013b;). However, according to the method of de Leva et al. (1996), the anthropometric data are calculated with the use of an anatomical model, meaning that the individual characteristics with respect to segmental flow fluctuations are not reflected with this method.
2.3.4.3. Mathematical models

Mathematical models have been developed for the representation of the human body. According to those models, each body segment of the human body is considered as being represented by a standard geometric shape.

The first attempts to develop mathematical models were conducted by Whitsett (1963) and Hanavan (1964). The former developed a 14-segment model, while the latter a 15-segment model. In these studies, the simple assumption of each segment being a single homogenous solid (such as right elliptical cylinder or frustum of a right circular cone) was adopted. Whitsett (1963) and Hanavan (1964) conducted anthropometric measurements in order to obtain the dimensions of the shapes and with the use of regression equations from cadaver data (Barter, 1957) estimated the segments’ mass. Regarding the validity tests of those two studies, Chandler et al. (1975) tested the model suggested by Hanavan against cadavers’ data and reported errors from 4.4 to 112.5% in moments of inertia. Chandler et al. (1975) concluded that the shapes used in the Hanavan model were not adequate to model the body segments. This statement was further supported by Jensen (1978), who stated that the validity of such models as the one suggested by Hanavan (1964) is questionable due to the extensive geometrical and mass distribution assumptions.

Jensen (1978) developed a model which was comprised of 16 segments. Each segment was subdivided by elliptical zones (2 cm wide) and this way, the shape fluctuations within the segment were reflected. The modelling of the body with the use of elliptical zones had been originally suggested by Weinbach (1938) and validated later by Dempster (1955). The latter researcher reported that using Weinbach’s model, results of very good accuracy were obtained with the exception of the shoulders. Jensen (1978) obtained the axes of the elliptical zones by photographing the participants in anatomical position from the front and side views simultaneously. The densities of each segment were considered uniform and the calculations
of the densities were based on the data from the literature. Although there is evidence that the assumption of uniform density is invalid along the segment’s length, the errors produced from this assumption in the calculation of inertial parameters are considered minor and acceptable (Ackland et al., 1988).

The validity of the elliptical zone method has been well established for different populations. Yokoi et al. (1985) tested children and reported errors smaller than 2% in the body mass values and body’s COM location between measured and estimated values from Jensen’s model, while Sanders et al. (1991) reported errors 0.35 ± 3.00% in the estimation of the body mass of participants aged 21-35 years. Moreover, Jensen and Fletcher (1994) reported errors of 0.05 ± 2.96% in the estimation of body mass in a sample of elderly participants. Furthermore, Wicke and Lopers (2003) assessed the validity of Jensen’s method in 20 university students (10 males and 10 females) of different morphologies. According to the researchers, three sources of error were considered: differences in body shape between males and females, image to actual body size ratios and human errors in the digitising process. According to the results, no significant differences were found between male and female participants in the segmental volumes estimations, which confirms that the elliptical zone method reflects accurately shape variations. The findings also showed that the volumes of segments as well as of the whole body can be accurately estimated with this method. Finally, the researchers suggested the use of larger image ratios for better accuracy in the estimation of the volumes. This suggestion was based on the findings that image ratio of 1:5 reduced the errors in volume estimation compared to smaller ratio of 1:10.

Despite the fact that the elliptical zone method is considered an accurate method for obtaining segmental parameters, the method has not been popular amongst the researchers due to the requirement of a large digitising table (Deffeyes and Sanders, 2005). Deffeyes and Sanders (2005) attempted to solve this problem by developing a computer-based digitising software,
called ‘e-Zone’, which uses the methods of Jensen (1978) and combines two processes: a) the digitising of the photographs required to obtain the diameters of the ellipses and b) the calculation of the body segments parameters. The e-Zone program has been validated by Psycharakis (2006) and McCabe (2008) who reported small differences between the estimated and actual body mass values. These findings were further supported by Sanders et al. (2015) who tested the between- and within-assessors reliability of the e-Zone program. The researchers reported less than 5% difference in within-assessor reliability and equal or larger errors in between-assessor reliability, and suggested that the individual should be assessed by the same assessor. The researchers concluded that the e-Zone program constitutes a reliable tool for obtaining body segment parameters data. Indeed, the e-Zone program has been used in 3D motion analyses in swimming in several studies (McCabe et al., 2011; McCabe and Sanders, 2012; Psycharakis and Sanders, 2009; Psycharakis et al., 2010). Based on the above, the e-Zone program will be used in the present study.

2.4. Summary of literature review

This study examines the effect of fatigue and skill level on kinematic characteristics of male sprint swimmers during an intermittent maximal training set. For this purpose, kinematic variables which have been linked with swimming performance will be assessed with the implementation of the most accurate methods.

From the literature review, it has been found that more skilled swimmers are characterised by larger V, SL and SI values in relation to less skilled swimmers, while SL has been recognised as the main discriminating factor accounting for the skill level and performance differences. Moreover, under fatigued conditions, higher skilled swimmers are able to maintain better their V in relation to the less skilled swimmers, as the former display a more constant SL when fatigued. Furthermore, as fatigue develops, the higher skilled swimmers display better
adaptability with respect to the temporal characteristics of their technique, as they allocate longer relative time in the propulsive phases of the stroke cycle. Limited and discrepant results exist with respect to the effect of skill level and fatigue on shoulder and hip roll, as data suggest that faster swimmers roll their shoulders less, while other data show no differences in shoulder roll magnitudes between swimmers of different skill levels. Thus, it is still uncertain whether and how the shoulder and hip roll magnitudes are linked with swimming performance. Complementarily, it has been suggested that fatigue results in increases in shoulder roll while hip roll remains unchanged, while according to other findings the hip roll increases and the shoulder roll remains constant under fatigue. Finally, the IVV is not affected by the development of fatigue, while it remains unclear whether IVV magnitude is positively or negatively associated with swim performance. Consequently, further investigation is required with respect to the association between IVV and performance.

While the aforementioned studies provided useful data on the effect of fatigue and skill level on the performance-related kinematic parameters, the majority of the studies tested the swimmers during races or race simulations, while in other studies, incremental tests, continuous constant-speed maximal tests, or short (>200-m) maximal tests were employed. This indicates that there is an important knowledge gap with respect to data in relation to the effect of fatigue and skill level during maximal intermittent training sets which are commonly used by the coaches in daily practice. This type of data will help coaches to design more effective training programs and also will provide guidance with respect to feedback orientation in terms of possible technique adjustments.

Finally, several limitations have been identified with respect to methodologies that have been employed in the existing studies. The investigation of kinematic parameters in swimming requires accurate and reliable techniques in order to minimise the errors. In the present study, the accuracy and reliability will be achieved by the implementation of the following methods:
3D motion analysis of the COM; accurate calculation of the anthropometric data; and digitising by one assessor so that the inter-assessor errors are eliminated.
3. Methodology

3.1. Participants

A total of 16 male swimmers who specialised in front crawl sprint or middle distance events (50-200-m) volunteered for this study. Participants consisted of senior swimmers of national and international level. The characteristics of the group, expressed as mean ± standard deviation (SD), were age 21.7 ± 3.4 years; height 1.85 ± 0.08 m; body mass 79.50 ± 8.51 kg and best performance in 100-m front crawl (short course) 51.20 ± 1.99 seconds. Participants’ anthropometric characteristics along with their performance data in 100-m front crawl (short course) are presented in Table 3.1. All swimmers had been training for at least 6 years at a minimum frequency of 6 sessions per week, prior to the study being conducted. The level and training experience of the participants ensured that they were familiar with high-intensity training and had good knowledge of nutrition and hydration. All swimmers did not have any injuries or health problems at the time the study was conducted. Swimmers who smoked or were taking any type of medication were not included in the study. Furthermore, the swimmers and their coaches were instructed to avoid any strenuous exercise the last two days prior the testing day, in order to ensure that there would be no interference with their performance at the testing protocol. Additionally, the swimmers were asked to follow their proper/normal diet the days before and on the testing day, also avoiding alcohol.

Before participation in the tests, the swimmers were informed about all procedures related to testing followed by signing a consent form. All test procedures were approved by the University of Edinburgh Ethics Committee.
<table>
<thead>
<tr>
<th>Participant</th>
<th>Age (years)</th>
<th>Height (m)</th>
<th>Body mass (kg)</th>
<th>PB 100-m FC (s)</th>
<th>PB 100-m FC (%WR)</th>
</tr>
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<tr>
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<tr>
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<tr>
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<td>58.3</td>
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</tr>
</tbody>
</table>

Table 3.1: Participants’ age, height, body mass, personal best time in 100-m front crawl (PB 100-m FC) and personal best time in 100-m front crawl expressed as percentile of the World Record (PB 100-m FC %WR).
3.2. Establishment of skill level

The participants were split into 2 groups (elite and sub-elite) based on their personal best times in the 100-m front crawl as shown in Table 3.1. The swimmers whose personal best time in the 100-m front crawl was at least 90% of the World Record time in this event were assigned to the elite group, while those swimmers whose personal best time in 100-m front crawl corresponded to a percentile smaller than 90% of the World Record time were assigned to the sub-elite group (Seifert et al., 2007a). Hence, the elite and sub-elite groups were consisted of 8 swimmers each. The descriptive characteristics of the elite and sub-elite group, expressed as mean ± SD, were as follows: age 20.9 ± 1.9 years and 22.4 ± 4.5 years; height 1.88 ± 0.05 m and 1.81 ± 0.09 m; body mass 82.9 ± 5.0 kg and 76.2 ± 10.2 kg; PB 100-m FC 49.48 ± 0.42 s and 52.92 ± 1.24 s; PB 100-m FC %WR 90.83 ± 0.77% and 84.96 ± 2.00% respectively.

3.3. Data collection

Each swimmer was asked to attend one testing session. This session consisted of: a) the collection of anthropometrical data and b) the collection of kinematical swimming data for the three-dimensional analysis.

3.3.1. Preparation of the participants for the data collection

The participants wore brief swimming suits (hip joint to be clearly visible) and caps (in order to eliminate any interference of hairstyle with the digitisation of head perimeter). The height and body mass of the participants were recorded with the use of Seca 213-1821009 stadiometer and Seca 712-1321009 weighting scales respectively. Black waterproof oil based body paint (Grimas Créme Make Up) applied by a sponge (45 mm diameter) was used to mark swimmers’ anatomical landmarks. The following landmarks were marked: vertex of the head (black paint on a white cap), shoulder, elbow, wrist, 3rd distal phalanx of the finger, hip, knee, ankle, 5th metatarsophalangeal joint and 1st interphalangeal joint of the toe. The aforementioned markers
were required for the kinematic analysis. For this reason, markers were also placed on the frontal and lateral aspects of the bespoke landmarks in order that the markers could be identified from more than one camera view.

Additional markers were required for the calculations of the anthropometric data with the use of elliptical zone method as described later in section 3.3.2. Those markers were added on the mandible angle, 2nd cervical vertebra, 7th cervical vertebra, axes of the head of humerus, acromioclavicular joint, greater trochanter of femur and the line of xiphoid process. For the aforementioned additional markers, black tape was used in order to be easily removed as those additional markers were not required for the kinematical analysis of the swimming trials.

3.3.2. Anthropometrical data collection

The anthropometric data of the swimmers were quantified by the elliptical zone method of Jensen (1978). This method was applied using the e-Zone program, which is a software written in MATLAB and developed by Deffeyes and Sanders (2005). With this method, the segments morphology are taken into account in order to calculate the segment parameter data for the subsequent calculation of the whole body COM. This method to be implemented requires two photographs of the participants to be taken simultaneously as: a) front and left views and b) front and right views.

3.3.2.1. Camera setup and capture

Two digital cameras (Sony DSC-V1 and Sony DSC-S730) with 8.0 mega pixel capacity were used in this study for capturing the participants. Although a capacity of 2.0 mega pixels is considered adequate for the data collection (Deffeyes and Sanders, 2005), the higher resolution cameras allowed a larger image to actual body size ratio which increased the accuracy of the subsequent digitising process of the body segments. The two cameras were set on horizontally levelled tripods at 1 m height in accordance with Deffeyes and Sanders (2005) that the height of the cameras should be set at an equivalent of one-half of the participant’s height. The
cameras were positioned so that their lines of sight were perpendicular to one another. For the minimization of image distortion while maintaining a large image of the participant, the cameras were positioned 6 m away from the participants set at a 3x optical zoom. Finally, with respect to cameras settings, the exposure time was set at 1/60 seconds and the ISO equivalent speed at 200.

Before the photographs of the participants were taken, the area was calibrated by taking photos of vertical and horizontal reference scales which were positioned in the plane corresponding to participants’ frontal and sagittal planes (Figure 3.1).

![Reference Scales](image)

Figure 3.1: Front view (left picture) and side view (right picture) of the reference scales.

The researchers ensured that no changes in the camera settings occurred between the photographing of the calibration and the participants. The participants stood on an inclined platform so that their ankles could be plantar flexed allowing a good frontal view of the feet.
for subsequent digitisation. The participants were required to stand in the anatomical position. This position was with their chin up (i.e. mandible being horizontal), fingers and thumb adducted with the palms facing the front camera, elbows extended and shoulders abducted with the arms back to allow for visibility of the back. After the swimmers were satisfactorily positioned, two photographs (front and side views) were taken simultaneously to eliminate errors due to the subject moving (Figure 3.2).

Figure 3.2: Front view (left picture) and side view (right picture) of the participant for e-Zone program.
3.3.3. Kinematical data collection

3.3.3.1. Swimming pool details

The swimming test took place in a six-lane indoor pool at the University of Edinburgh. The dimensions of the pool were 25 m x 13.25 m x 2 m (length x width x depth). Throughout the testing period, the pool temperature was about 29 °C while the ambient temperature was approximately 30 °C. During the testing sessions, the pool was used only by the investigators and only one swimmer at a time was allowed in the pool in order to avoid any interference with camera views by wave turbulence. The pool was level deck and therefore the wave turbulence was minimal.

3.3.3.2. Camera settings

Six stationary gen-locked ELMO PTC-400c cameras (four underwater and two above water) were used to record the motion of the swimmers. The cameras were connected to a six channel recording system (i.e. six channels of hard disk recording) and were operating at 25 fields per second with the electronic shutter speed at 1/120 seconds. Whereas sampling frequencies of 25-50 fields per second are recommended for swimming motion analysis (Payton and Bartlett, 2008; pp. 22), the sampling frequency of the present study (25 fields per second) constitutes a potential limitation, as in the majority of swimming studies frequencies of 50 fields per second were employed (Barbosa et al., 2005; 2013; Figueiredo et al., 2012a; 2012b; McCabe et al., 2011; Psycharakis et al., 2010; Schnitzler et al., 2010; Seifert et al., 2007a).

3.3.3.3. Calibration frame

The recorded swimming space was calibrated by a calibration frame which was manufactured by the University of Edinburgh for the purposes of three-dimensional motion analysis (Figure 3.3). The calibration frame was a rectangular prism and the dimensions were: 4.5 m length, 1.5 m height and 1.0 m width (total volume of 6.75 m³). A total of 92 polystyrene spheres of
3 cm diameter were randomly distributed in the frame. Those spheres were serving as control points.

![Picture of the calibration frame](image)

**Figure 3.3: Picture of the calibration frame.**

Prior to the testing session, the calibration frame was placed in the middle of the swimming pool. Eight aluminium legs (1.25 m in length) were screwed to the bottom of the frame so that the frame was elevated with half of it being equally above and below the water surface. The frame was aligned with the external frame of the pool with the x axis in the swimming direction.

Psycharakis et al. (2005) established high accuracy and reliability of three-dimensional coordinate calculation. With respect to accuracy, Psycharakis et al. (2005) using 10 control points reported that for a set of 30 digitised points the average difference was 3.3 mm, 2.6 mm and 4.0 mm for the x, y and z axes respectively with the average root mean square errors for these points being 3.9 mm for x axis, 3.8 mm for y axis, and 4.8 mm for the z axis respectively, representing 0.1%, 0.2% and 0.5% of the calibrated space. Therefore, Psycharakis et al. (2005) stated that the accuracy of the frame in this study was similar or better than other frames used in three-dimensional swimming studies. The reliability test by Psycharakis et al. (2005) indicated good reliability in the reconstruction of three dimensional coordinates as after
repeated digitisations of one control point the differences were \( \pm 0.4 \) mm, \( \pm 0.5 \) mm and \( \pm 0.4 \) mm for x, y, and z axes respectively.

### 3.3.3.4. Camera set up for testing

The six cameras used in this study were placed according to Psycharakis (2006). The four below water cameras were positioned at various depths (from 0.5 m to 1.5 m under the water surface) so that errors related to the cameras axes being in the same planes as the axes of the calibration were avoided. The above water cameras were mounted at 3 m height on the side walls of the swimming hall. The underwater and above water cameras were set approximately 8 m and 12 m respectively away from the centre of the calibrated space. The approximate positions of the cameras are shown in Figure 3.4.
Figure 3.4: Camera and calibration frame setup for the testing session of three-dimensional motion analysis. Cameras 1, 2, 3 and 4 are underwater. Cameras 5 and 6 are above water. X, Y, and Z are horizontal, vertical, and lateral directions respectively. Adapted from Pscharakis (2006).

As suggested by Pscharakis (2006), the angle between axes of the underwater cameras varied from 75° to 110°, while the angle between the two above water cameras axes were approximately 100°. The settings of the cameras were adjusted in order to record a 6.5 m long
space (extending 1 m beyond each side of the 4.5 m long calibration frame for the horizontal axis) as shown in Figure 3.5. The latter setting ensured that at least one complete stroke cycle was recorded and a large image of the swimmer was available for the data analysis and digitising.

Figure 3.5: Cameras’ field of view. Cameras 1, 2, 3 and 4 are underwater. Cameras 5 and 6 are above water. Adapted from Pscharakis (2006).

After the cameras were adjusted as described, the calibration frame was recorded for approximately 10 seconds (no one in the water during the recording). Following the aforementioned recording, the frame was removed from the water and 2 black blocks were
placed on the bottom of the pool in order to outline the calibrated space. The positions of the cameras and their settings were not changed at any point thereafter until the completion of the entire testing session.

### 3.3.3.5. Swimming protocol

The participants carried out an individual warm up of approximate 1500-m including low-moderate intensity aerobic swimming, drills, sprints, and pace swimming. After the warm up, each swimmer performed a set of 12 trials of 50-m front crawl at maximum intensity. In detail, the swimmers were asked to execute the first trial at a pace corresponding to their second 50-m of their 100-m personal best performance and then try to maintain, to the extent they were capable of, that pace across the 12 trials. After the completion of each trial, feedback regarding the performance achieved with respect to time and stroke frequency was given using a manual stopwatch. It should be noted that the provided feedback with respect to stroke frequency is a potential limitation of the study as the swimmers might have used this feedback to adjust their technique during the testing. The work to rest ratio for the trials was 1:1.5 (Maglischo, 2003; pp. 475-478). This swimming protocol was selected for the following reasons:

a) The characteristics of the aforementioned type of sets result in high levels of exercise-induced fatigue (Peyrebrune et al., 2014).

b) This type of training set is typically recommended for the development of a swimmer’s ability to perform at the required pace and stroke frequency for the 100-m front crawl event (Maglischo, 2003; pp. 475-478).

c) This type of training set is widely used among swimming coaches (Maglischo, 2003; pp. 475-478).

The participants performed the aforementioned 12 trials in the centre of the swimming pool (calibrated space) and initiated each trial with a push-off start in order to eliminate any possible impact of a dive on the kinematic characteristics of the first length of each trial. The swimmers
were required not to breathe within the outlined calibrated space in the second 25-m of each trial which was subsequently analysed.

3.4. Data processing and analysis

3.4.1. Anthropometric parameters calculation

The anthropometric data collected was processed with the e-Zone program in MATLAB version R2014a (Math Works, Inc., Natick, Massachusetts, USA). Firstly, the photographs of the reference scales were uploaded in the program and then the dimensions of the scales were defined. Secondly, the photographs of the swimmers were uploaded and the anatomical landmarks from front and side views were identified. Finally, the following body segment clusters were outlined/digitised (with the use of MATLAB image processing): head and neck; thorax and abdomen; thigh, shank and foot (lower limb); and upper arm, forearm and hand (upper limb). Based on the digitisation of the body segment clusters, the e-Zone program produced a model (representing the participant) which was divided into the head, neck, thorax, arm, forearm, hand, thigh, shank, and foot segments as shown in Figure 3.6.

![Figure 3.6: Model produced by the e-Zone program: front (left picture) and side (right picture) views.](image-url)
3.4.2. Digitising of swim trials

The video files from the camera recordings of the swim trials were stored in the aforementioned six-channel recording system in an AVI format. All AVI files were transferred into a separate computer for digitising and calculation of the three-dimensional coordinates with the use of Ariel Performance Analysis System (APAS) software (Ariel Dynamics, Inc., California, USA).

Due to the large number of trials (12) and time constraints, every 2\textsuperscript{nd} trial, starting from the first trial, was selected for kinematic analysis (trials 1; 3; 5; 7; 9; 11). The hypothesis was that both the elite and sub-elite swimmers were highly trained and the differences in kinematics between consecutive trials would be minimal if existent.

The first stage of the data processing was the selection of one complete stroke cycle for each one of the 50-m trials. To obtain this stroke cycle, the start and end points were defined as the video frames at which the 3\textsuperscript{rd} metacarpal tip of the same hand entered the water two consecutive times. The hand entry which was selected as the starting point of the stroke cycle was based on the first to enter the water in the calibrated space with the whole body of the swimmer also in view. After the stroke cycles of each trial were defined, the video files of all 6 cameras were trimmed accurately using the time codes displayed on each camera view.

The next stage of the data processing was the creation of 2 sequence files (above and below water) by which the body landmarks to be identified along with the calibration points were defined. In this study, 20 calibration points were selected as in Psycharakis (2006). After the sequence files were created, the following body landmarks of the swimmers were manually digitised: vertex of the head; left and right finger, wrist, elbow, shoulder, hip, ankle 5\textsuperscript{th} metatarsophalangeal joint and 1\textsuperscript{st} interphalangeal joint. The same digitising procedure was followed for each frame within the stroke cycle for all 6 camera views.
Following the digitisation of each stroke cycle, the APAS Transform function was used for each stroke cycle in order to produce the raw three-dimensional coordinates for the above and below water views. This function of APAS is based on calculations from the Direct Linear Transformation method (DLT) method (Abdel-Aziz and Karara, 1971).

The final stage of data processing in APAS was the use of Display function in order to produce the displacement data (raw data) in x, y, and z axes for all digitised body landmarks. The output from this function were 2 files, one for above and one for below water views. The output files were then merged and saved in an excel file. The excel file was then exported as a txt file.

3.5. Calculation of variables

3.5.1. Calculation of anthropometric variables

The aforementioned e-Zone program calculated the mass and volume of each segment. Additionally, the e-Zone program calculated the location of the segment’s centre of mass in relation to each segment’s endpoints.

3.5.2. Calculation of kinematic variables

The calculation of all the kinematic variables was conducted with the use of a program written in MATLAB developed by Sanders (2013). This program required the input of the anthropometric and displacement data obtained from the data processing and analysis stage as previously described. For the acquisition of the kinematic variables, the anthropometric and displacement data were input into the MATLAB program as text files. This procedure was followed for all the 16 participants for each one of the 6 stroke cycles that were analysed.
As in Psycharakis et al. (2010), the raw displacement data acquired from APAS were filtered and smoothed with the use of a Fourier transform and inverse transform by retaining harmonics up to 6 Hz in the inverse transform.

After the calculation of the kinematic variables in MATLAB, all output data were expressed as percentiles corresponding to the beginning (0%) and the end (100%) of the stroke cycle. The output data were also expressed as real time. The expression of the output data both as percentile of the stroke cycle and in real time would enable comparisons of kinematic variables between stroke cycles of different durations.

### 3.5.2.1. Average swimming velocity, stroke length, stroke frequency, stroke index

The average horizontal swimming velocity (m·s⁻¹) was obtained by dividing the swimmer’s mean COM displacement during the stroke cycle by the duration of the stroke cycle. The stroke length (m) was defined as the displacement of the COM in the direction of swimming (horizontal) during a complete stroke cycle. The stroke frequency (cycles·min⁻¹) was calculated as the inverse of the time (in seconds) it took the swimmers to complete a stroke cycle which was then multiplied by 60. The stroke index (m²·cycles⁻¹·min⁻¹) was calculated as the product of the stroke length and average swimming velocity (McCabe, 2008).

These variables were calculated to display possible differences between the elite and sub-elite group and also how those performance variables changed across the trials.

### 3.5.2.2. Stroke phase durations

Each stroke cycle was divided into 5 phases as follows:

a) Entry phase: from the time that the finger enters the water to the time of the first backward movement of the finger (McCabe, 2008).
b) Pull phase: from the time of the first backward movement of the finger to the time the finger is vertically aligned with the shoulder joint (McCabe, 2008).

c) Push phase: from the time of the finger in line with the shoulder joint until the time the finger starts moving to the opposite horizontal direction in relation to the beginning of this phase.

d) Release: from the end point of the push phase until the finger exits the water.

e) Recovery phase: from the time the finger exits the water until the point of the next entry of the finger.

The duration of each phase was quantified and then expressed as a percentile in relation to the duration of the stroke cycle (relative duration). It should be highlighted that the analysed stroke cycles for each swimmer did not always begin with the same hand and therefore potential individual bilateral asymmetries were not considered. This is a potential limitation of the present study given that the stroke phases are dependent upon bilateral asymmetries (Nikodelis et al., 2005).

3.5.2.3. Shoulder and hip roll

As in McCabe (2008), the shoulder roll angle (degrees) during the stroke cycle was defined as the angle between the unit vector of the line connecting the shoulder joint-centres that was projected onto the YZ plane and the horizontal. The hip roll angle (degrees) was determined in the same manner as the shoulder roll except that the unit vector was the line connecting the hip joints. The equations of the calculations of shoulder and hip roll angles were as follows:

\[
\text{Shoulder roll angle} = \arctan\left(\frac{S_z}{S_y}\right)
\]

Where \(S_z\) and \(S_y\) are the z and y components respectively of the shoulder unit vector.

The hip roll angle was calculated as:

\[
\text{Hip roll angle} = \arctan\left(\frac{H_z}{H_y}\right)
\]

Where \(H_z\) and \(H_y\) are the z and y components respectively of the hip unit vector.
During each stroke cycle of interest, the maximum shoulder and hip roll angles were determined for both the right and left sides. The greater maximum shoulder/hip roll angle between the two sides was used for the data analysis and, as speculated above (section 3.5.2.2), bilateral asymmetries related to handedness constitute a potential limitation (Pscharakis and Sanders, 2008).

3.5.2.4. Intracycle Velocity Variations
According to Pscharakis (2006) the centre of mass (COM) displacement (cm) was determined by the standard procedure of summing moments of the segment centres of mass about the x, y, and z reference axes. The velocity of the COM (m·s⁻¹) was then quantified by differentiating the COM displacement data by the use of the first central difference formula. The maximum and minimum instantaneous velocities were obtained from the intracycle velocity data of the COM. The intracycle velocity variations (IVV) in the x, y, and z axes were calculated by subtracting the absolute minimum from the maximum instantaneous velocities of the COM in each stroke cycle. The IVV in each direction was also calculated as a percentage of the average velocity of the COM in the direction of swimming (Vmeanx).

3.6. Statistical analysis
The Statistical Package for Social Sciences (SPSS) version 19.0 (IBM Corporation, Somers, NY, USA) was used for the analysis of the data. Means and standard deviations were calculated for all the variables of interest. Normal distribution of the data was verified by the Shapiro-Wilk’s test. A two-way ANOVA (trial × skill level) with repeated measures was performed in this study in order to compare the elite and sub-elite groups across the 6 trials of interest. Sphericity was verified by the Mauchly test. When the sphericity was violated, adjustments according to the Greenhouse-Geisser procedure were made (Field, 2009). The repeated measures ANOVAs were completed by Bonferroni post-hoc tests. The effect sizes
were defined according to Richardson (2011) with partial eta squared ($\eta^2$) values equal to 0.0099, 0.0589 and 0.1379 representing small, medium and large effect sizes respectively. Statistical significance was set at p<0.05.
4. Results

In this section, the results of the parameters of interest are presented. Tables and graphs are used to visualise the results and highlight the differences between the elite and the sub-elite group over the course of the 6 trials (trial 1, trial 3, trial 5, trial 7, trial 9 and trial 11) that were analysed.

4.1. Accuracy and reliability tests

4.1.1. Accuracy and reliability of e-Zone program

The reliability of the variables obtained from e-Zone was tested based on 4 participants that were digitised five times each. The Intra-class Correlation Coefficient (ICC) test was employed to assess the reliability of the aforementioned 5 trials. In addition to ICC, the percent coefficient of variation (CV%) was calculated to show the extent of variability in relation to mean values. Furthermore, the 95% confidence intervals (95% CI) were calculated to display the range in which the true value of each variable fell 95% of the time. Table 4.1 shows the results from reliability assessment of the e-Zone. The ICC values for 13 of 14 anatomical segments were higher than 0.95 which indicates that the variables obtained from e-Zone appear to be highly reproducible. The fact that only one segment was found to have an ICC below 0.9, can be mainly attributed to the difficulty in outlining particular body segments such as the hand, consistently. CV% values were considered low and acceptable for most variables.

The accuracy of the e-Zone program was quantified by measuring the difference between the body mass of all the participants as was estimated by the e-Zone program, to that obtained from the weighing scales on the day of testing. It was found that the mean ± SD differences between e-Zone’s estimations and the actual body mass values (measured from the weighing
scales) were -0.34 ± 0.30 kg corresponding to a percentage -0.54 ± 0.54% of the actual body mass values. These results show high accuracy as it was reported by Psycharakis (2006) and McCabe (2008).

**4.1.2. Reliability of calculated variables**

The reliability of the calculated variables was tested based on the same stroke cycle being digitized five times. For this reliability assessment, mean values, standard deviations (SD), CV% and 95% CI were calculated. The results of the reliability test are presented in Table 4.2. The CV% values were considered low and acceptable for all the parameters (all below 3%). No results are presented for Vminy nor Vminz due to the fact that the SD of those variables was 0.
<table>
<thead>
<tr>
<th>Region</th>
<th>mean</th>
<th>SD</th>
<th>95% CI</th>
<th>CV%</th>
<th>ICC segment mass</th>
<th>ICC %COM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head and neck</td>
<td>5.703</td>
<td>0.100</td>
<td>5.616-5.791</td>
<td>1.753</td>
<td>0.979</td>
<td>0.928</td>
</tr>
<tr>
<td>Trunk</td>
<td>32.294</td>
<td>0.103</td>
<td>32.204-32.384</td>
<td>0.317</td>
<td>0.999</td>
<td>0.995</td>
</tr>
<tr>
<td>Left arm</td>
<td>2.125</td>
<td>0.015</td>
<td>2.111-2.138</td>
<td>0.703</td>
<td>0.957</td>
<td>0.808</td>
</tr>
<tr>
<td>Left forearm</td>
<td>1.014</td>
<td>0.008</td>
<td>1.007-1.020</td>
<td>0.753</td>
<td>0.975</td>
<td>0.925</td>
</tr>
<tr>
<td>Left hand</td>
<td>0.478</td>
<td>0.006</td>
<td>0.473-0.483</td>
<td>1.188</td>
<td>0.856</td>
<td>0.827</td>
</tr>
<tr>
<td>Left thigh</td>
<td>7.602</td>
<td>0.030</td>
<td>7.576-7.628</td>
<td>0.389</td>
<td>0.999</td>
<td>0.709</td>
</tr>
<tr>
<td>Left shank</td>
<td>3.089</td>
<td>0.042</td>
<td>3.052-3.126</td>
<td>1.356</td>
<td>0.990</td>
<td>0.964</td>
</tr>
<tr>
<td>Left foot</td>
<td>0.841</td>
<td>0.033</td>
<td>0.812-0.869</td>
<td>3.900</td>
<td>0.987</td>
<td>0.899</td>
</tr>
<tr>
<td>Right arm</td>
<td>2.115</td>
<td>0.023</td>
<td>2.095-2.135</td>
<td>1.093</td>
<td>0.975</td>
<td>0.872</td>
</tr>
<tr>
<td>Right forearm</td>
<td>1.113</td>
<td>0.021</td>
<td>1.095-1.132</td>
<td>1.929</td>
<td>0.966</td>
<td>0.960</td>
</tr>
<tr>
<td>Right hand</td>
<td>0.611</td>
<td>0.008</td>
<td>0.604-0.618</td>
<td>1.351</td>
<td>0.966</td>
<td>0.960</td>
</tr>
<tr>
<td>Right thigh</td>
<td>7.600</td>
<td>0.075</td>
<td>7.534-7.666</td>
<td>0.985</td>
<td>0.998</td>
<td>0.783</td>
</tr>
<tr>
<td>Right shank</td>
<td>3.579</td>
<td>0.073</td>
<td>3.514-3.643</td>
<td>2.048</td>
<td>0.987</td>
<td>0.964</td>
</tr>
<tr>
<td>Right foot</td>
<td>0.937</td>
<td>0.027</td>
<td>0.914-0.961</td>
<td>2.856</td>
<td>0.970</td>
<td>0.799</td>
</tr>
</tbody>
</table>

Table 4.1: Results of the reliability test of e-Zone program (SD, Standard Deviation; CI, Confidence Interval; CV%, percent Coefficient of Variation; ICC, Intra-class Correlation Coefficient; %COM, segment’s centre of mass position as a percentage of segment’s length).
<table>
<thead>
<tr>
<th>Variable</th>
<th>mean</th>
<th>SD</th>
<th>CV%</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average swimming velocity (m·s⁻¹)</td>
<td>1.75</td>
<td>0.02</td>
<td>0.88</td>
<td>1.73-1.76</td>
</tr>
<tr>
<td>Stroke length (m)</td>
<td>2.55</td>
<td>0.02</td>
<td>0.85</td>
<td>2.50-2.60</td>
</tr>
<tr>
<td>Stroke frequency (cycles·min⁻¹)</td>
<td>41.61</td>
<td>0.37</td>
<td>0.89</td>
<td>41.29-41.93</td>
</tr>
<tr>
<td>Stroke index (m²·cycles⁻¹·min⁻¹)</td>
<td>4.45</td>
<td>0.06</td>
<td>1.30</td>
<td>4.40-4.51</td>
</tr>
<tr>
<td>Relative entry duration (%)</td>
<td>25.53</td>
<td>0.05</td>
<td>0.18</td>
<td>25.49-25.57</td>
</tr>
<tr>
<td>Relative pull duration (%)</td>
<td>22.01</td>
<td>0.04</td>
<td>0.20</td>
<td>21.97-22.05</td>
</tr>
<tr>
<td>Relative push duration (%)</td>
<td>21.37</td>
<td>0.03</td>
<td>0.13</td>
<td>21.35-21.40</td>
</tr>
<tr>
<td>Relative release duration (%)</td>
<td>5.21</td>
<td>0.03</td>
<td>0.61</td>
<td>5.18-5.24</td>
</tr>
<tr>
<td>Relative recovery duration (%)</td>
<td>25.91</td>
<td>0.08</td>
<td>0.31</td>
<td>25.84-25.98</td>
</tr>
<tr>
<td>Shoulder roll (degrees)</td>
<td>50.74</td>
<td>0.35</td>
<td>0.69</td>
<td>50.43-51.05</td>
</tr>
<tr>
<td>Hip roll (degrees)</td>
<td>30.20</td>
<td>0.16</td>
<td>0.52</td>
<td>30.06-30.34</td>
</tr>
<tr>
<td>Vmaxx (m·s⁻¹)</td>
<td>2.06</td>
<td>0.02</td>
<td>0.77</td>
<td>2.05-2.07</td>
</tr>
<tr>
<td>Vminx (m·s⁻¹)</td>
<td>1.51</td>
<td>0.02</td>
<td>0.98</td>
<td>1.50-1.53</td>
</tr>
<tr>
<td>Vmaxy (m·s⁻¹)</td>
<td>0.46</td>
<td>0.01</td>
<td>2.50</td>
<td>0.45-0.47</td>
</tr>
<tr>
<td>Vmaxz (m·s⁻¹)</td>
<td>0.57</td>
<td>0.02</td>
<td>2.64</td>
<td>0.56-0.59</td>
</tr>
</tbody>
</table>

Table 4.2: Results of reliability test of the calculated variables (SD, Standard Deviation; CV%, percent Coefficient of Variation; CI, confidence interval).
4.2. Average swimming velocity

Figure 4.1 illustrates the average horizontal swimming velocity of the COM for the elite and sub-elite group over the course of the 6 trials of interest. Table 4.3 shows the results of the statistical analysis. Significant main effect of Trial with large effect size (p=0.004, \(\eta^2=0.364\)) was found as participants’ average swimming velocity in trial 11 dropped by 5.3%, 3.6% and 3.0% compared to trial 1 (p=0.050), trial 3 (p=0.049) and trial 5 (p=0.015) respectively. Moreover, the statistical analysis revealed significant main effect of Skill level with large effect size (p<0.001, \(\eta^2=0.602\)) as, over the course of the 6 trials, the elite group produced an average swimming velocity of 1.74 m·s\(^{-1}\) while the sub-elite group produced 1.59 m·s\(^{-1}\).

Furthermore, the interaction trial × skill level was found to be significant with large effect size (p=0.029, \(\eta^2=0.160\)) as the elite swimmers produced significantly greater average swimming velocities (p<0.01) than the sub-elite ones in each of the 6 trials.

![Figure 4.1: Average swimming horizontal velocity of the elite and sub-elite group over the course of the 6 trials (** significant difference between groups p<0.01). Error bars represent the standard deviation.](image)

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<table>
<thead>
<tr>
<th></th>
<th>df</th>
<th>F-ratio</th>
<th>Significance (p)</th>
<th>Effect size (partial (\eta^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial</td>
<td>5, 70</td>
<td>8.021</td>
<td>0.004</td>
<td>0.364</td>
</tr>
<tr>
<td>Skill level</td>
<td>1, 14</td>
<td>21.134</td>
<td>&lt;0.001</td>
<td>0.602</td>
</tr>
<tr>
<td>Trial x skill level</td>
<td>5, 70</td>
<td>2.664</td>
<td>0.029</td>
<td>0.160</td>
</tr>
</tbody>
</table>

Table 4.3: Results of the repeated measures ANOVA for average swimming horizontal velocity (df, degrees of freedom).

4.3. Stroke length

Figure 4.2 shows the stroke length values for the elite and sub-elite groups in the 6 trials of interest. The ANOVA, as it is illustrated in Table 4.4, revealed significant main effects of Trial (\(p<0.001\)) and Skill level (\(p=0.006\)) with large effect sizes (\(\eta^2=0.331\) and \(\eta^2=0.138\) respectively). With respect to main effect of Trial, the stroke length significantly decreased by 4.0% in trial 7 (\(p=0.04\)) and 4.9% trial 11 (\(p=0.01\)) compared to trial 1. Furthermore, the stroke length was found to be shorter by 3.6% in trial 7 compared to trial 3 (\(p=0.020\)). Regarding the main effect of Skill level, the elite swimmers were found to produce on average 10.0% longer stroke length compared to the sub-elite swimmers over the course of the 6 trials as the elite swimmers produced significantly greater stroke lengths (\(p<0.01\)) in all the trials. However, the stroke length values were not normalised to height which would have decreased significantly the differences in stroke length values between the elite and the sub-elite group. Additionally, significant interaction trial \(\times\) skill level was found with large effect size (\(p=0.029, \eta^2=0.160\)).
Figure 4.2: Stroke length of the elite and sub-elite group over the course of the 6 trials (** significant difference between groups p<0.01). Error bars represent the standard deviation.

<table>
<thead>
<tr>
<th></th>
<th>df</th>
<th>F-ratio</th>
<th>Significance (p)</th>
<th>Effect size (partial η²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial</td>
<td>5, 70</td>
<td>6.939</td>
<td>&lt;0.001</td>
<td>0.331</td>
</tr>
<tr>
<td>Skill level</td>
<td>1, 14</td>
<td>2.237</td>
<td>0.006</td>
<td>0.138</td>
</tr>
<tr>
<td>Trial x skill level</td>
<td>5, 70</td>
<td>2.664</td>
<td>0.029</td>
<td>0.160</td>
</tr>
</tbody>
</table>

Table 4.4: Results of the repeated measures ANOVA for stroke length (df, degrees of freedom).

4.4. Stroke frequency

Figure 4.3 displays the stroke frequency values of the participants in the 6 trials. The ANOVA results, as shown in Table 4.5, did not reveal any significant main effects of Trial (p=0.687, η²=0.032 small) nor Skill level (p=0.376, η²=0.056 small). There was also no significant interaction trial × skill level with small effect size (p=0.761, η²=0.025).
Figure 4.3: Stroke frequency of the elite and sub-elite group over the course of the 6 trials. Error bars represent the standard deviation.

<table>
<thead>
<tr>
<th></th>
<th>df</th>
<th>F-ratio</th>
<th>Significance (p)</th>
<th>Effect size (partial η²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial</td>
<td>5, 70</td>
<td>0.463</td>
<td>0.687</td>
<td>0.032</td>
</tr>
<tr>
<td>Skill level</td>
<td>1, 14</td>
<td>0.838</td>
<td>0.376</td>
<td>0.056</td>
</tr>
<tr>
<td>Trial x skill level</td>
<td>5, 70</td>
<td>0.355</td>
<td>0.761</td>
<td>0.025</td>
</tr>
</tbody>
</table>

Table 4.5: Results of the repeated measures ANOVA for stroke frequency (df, degrees of freedom).

4.5. Stroke index

Figure 4.4 illustrates the stroke index of the swimmers in the 6 trials. There were significant main effects of Trial (p<0.001) and Skill level (p=0.001) with large effect sizes of η²=0.446 and η²=0.536 respectively as displayed in Table 4.6. The swimmers of both groups displayed significantly higher stroke index values in trial 1 compared to trial 7 (p=0.001), trial 9 (p=0.05)
and trial 11 (p=0.003) with the stroke index in trial 1 being greater than in trials 7, 9 and 11 by 7.3%, 6.8% and 9.2% respectively. Moreover, the stroke index dropped significantly by 5.3% and 7.2% in trials 7 (p=0.033) and 11 (p=0.044) respectively compared to trial 3. Furthermore, significant decrease by 4.1% and 6.0% in stroke index was found in trial 7 (p=0.041) and trial 11 (p=0.015) compared to trial 5. Regarding the main effect of Skill level, the elite group displayed on average 18.3% greater stroke index values than the sub-elite group over the course of the 6 trials. In addition, significant interaction trial × skill level was found with large effect size (p=0.004, η²=0.217) as the elite swimmers displayed significantly greater stroke index in all the 6 trials (p<0.05 for trial 1 and p<0.01 for trials 3, 5, 7, 9 and 11).

Figure 4.4: Stroke index of the elite and sub-elite group over the course of the 6 trials (* significant difference between groups p<0.05, ** significant difference between groups p<0.01). Error bars represent the standard deviation.
<table>
<thead>
<tr>
<th></th>
<th>df</th>
<th>F-ratio</th>
<th>Significance (p)</th>
<th>Effect size (partial $\eta^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial</td>
<td>5, 70</td>
<td>11.291</td>
<td>&lt;0.001</td>
<td>0.446</td>
</tr>
<tr>
<td>Skill level</td>
<td>1, 14</td>
<td>16.152</td>
<td>0.001</td>
<td>0.536</td>
</tr>
<tr>
<td>Trial x skill level</td>
<td>5, 70</td>
<td>3.874</td>
<td>0.004</td>
<td>0.217</td>
</tr>
</tbody>
</table>

Table 4.6: Results of the repeated measures ANOVA for stroke index (df, degrees of freedom).

### 4.6. Stroke phase durations

#### 4.6.1. Entry phase

Figure 4.5 shows the relative duration of the entry phase expressed as the percentile of the duration of the stroke cycle. Table 4.7 illustrates the results from ANOVA. Significant main effect of Skill level with large effect size ($p=0.015$, $\eta^2=0.354$) was found from the statistical analysis as, across the 6 trials, the sub-elite swimmers spent on average 9.4% longer relative time in the entry phase compared to the elite swimmers. No significant main effect of Trial ($p=0.322$) with medium effect size ($\eta^2=0.079$) was found. The interaction trial × skill level was also non-significant ($p=0.636$) with medium effect size ($\eta^2=0.047$).
Figure 4.5: Relative entry duration across the 6 trials. Error bars represent the standard deviation.

<table>
<thead>
<tr>
<th></th>
<th>df</th>
<th>F-ratio</th>
<th>Significance (p)</th>
<th>Effect size (partial η²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial</td>
<td>2.745,</td>
<td>1.197</td>
<td>0.322</td>
<td>0.079</td>
</tr>
<tr>
<td></td>
<td>38.436</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skill level</td>
<td>1, 14</td>
<td>7.667</td>
<td>0.015</td>
<td>0.354</td>
</tr>
<tr>
<td>Trial x skill level</td>
<td>2.745,</td>
<td>0.685</td>
<td>0.554</td>
<td>0.047</td>
</tr>
<tr>
<td></td>
<td>38.436</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.7: Results of the repeated measures ANOVA for relative entry duration (df, degrees of freedom).
4.6.2. Pull phase

Figure 4.6 shows the relative duration of the pull phase expressed as the percentile of the duration of the stroke cycle. Table 4.8 illustrates the results from the statistical analysis. As it can be seen in Table 4.8, significant main effect of Trial was found with large effect size ($p=0.026$, $\eta^2=0.223$) as the swimmers spent 2.7% longer time in the pull phase in trial 7 compared to trial 11 ($p=0.005$). Furthermore, significant main effect of Skill level with large effect size ($p=0.002$, $\eta^2=0.497$) was revealed from the ANOVA with the elite swimmers spending significantly longer time (22.3%) in this phase. The interaction trial × skill level was not statistically significant ($p=0.106$) and the effect size was large ($\eta^2=0.145$).

![Figure 4.6: Relative pull duration across the 6 trials. Error bars represent the standard deviation.](image)
<table>
<thead>
<tr>
<th></th>
<th>df</th>
<th>F-ratio</th>
<th>Significance (p)</th>
<th>Effect size (partial $\eta^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial</td>
<td>2.155, 30.176</td>
<td>4.022</td>
<td>0.026</td>
<td>0.223</td>
</tr>
<tr>
<td>Skill level</td>
<td>1, 14</td>
<td>13.860</td>
<td>0.002</td>
<td>0.497</td>
</tr>
<tr>
<td>Trial x skill level</td>
<td>2.155, 30.176</td>
<td>2.381</td>
<td>0.106</td>
<td>0.145</td>
</tr>
</tbody>
</table>

Table 4.8: Results of the repeated measures ANOVA for relative pull phase (df, degrees of freedom).

4.6.3. Push phase

The relative duration of push phase is illustrated in Figure 4.7 and Table 4.9 shows the results of the statistical analysis for this variable. The statistical analysis revealed significant main effect of Trial with large effect size ($p=0.007$, $\eta^2=0.312$). The participants allocated shorter time by 3.0% in trial 9 ($p=0.004$) and by 4.2% in trial 11 ($p<0.001$) compared to trial 5. Similarly, the relative duration of push phase was found to be by 2.7% and 3.9% shorter in trials 9 and 11 respectively in relation to trial 7 ($p=0.024$ and $p=0.004$ compared to trials 9 and 11 respectively). The main effect of Skill level was also significant with large effect size ($p=0.003$, $\eta^2=0.484$) as, across the 6 trials, the elite swimmers spent the 22.0% of the stroke cycle in this phase whereas the sub-elite swimmers spent the 18.3%. No significant interaction trial × skill level ($p=0.307$) with medium effect size ($\eta^2=0.080$) was found for the push phase.
Figure 4.7: Relative push duration across the 6 trials. Error bars represent the standard deviation.

<table>
<thead>
<tr>
<th></th>
<th>df</th>
<th>F-ratio</th>
<th>Significance (p)</th>
<th>Effect size (partial $\eta^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial</td>
<td>1.814, 25.395</td>
<td>6.344</td>
<td>0.007</td>
<td>0.312</td>
</tr>
<tr>
<td>Skill level</td>
<td>1.14</td>
<td>13.138</td>
<td>0.003</td>
<td>0.484</td>
</tr>
<tr>
<td>Trial x skill level</td>
<td>1.814, 25.395</td>
<td>1.224</td>
<td>0.307</td>
<td>0.080</td>
</tr>
</tbody>
</table>

Table 4.9: Results of the repeated measures ANOVA for relative push phase (df, degrees of freedom).

4.6.4, Release phase

Figure 4.8 shows the relative duration of the release phase expressed as the percentile of the duration of the stroke cycle. As it can be seen in Table 4.10 which presents the results of the statistical analysis, there was significant main effect of Trial with large effect size ($p=0.001$, $\eta^2=0.368$). The relative time spent in the release phase increased by 5.5% in trial 7 ($p=0.008$), 14.9% in trial 9 ($p<0.001$) and 18.9% in trial 11 ($p<0.001$) compared to trial 5. Similarly, the participants spent 8.9% and 12.6% longer relative time in trial 9 ($p=0.007$) and trial 11.
(p=0.001) respectively in relation to trial 7. However, as it can be seen in figure 4.18, these increases in the duration of the release phase as the test progressed are due to the changes observed in the temporal characteristics of the sub-elite swimmers, as the elite swimmers’ release duration remained unchanged. Significant main effect of Skill level was also revealed from the statistical analysis with large effect size (p=0.002, $\eta^2=0.507$). Across the 6 trials, the sub-elite swimmers allocated an average of 8.8% of the stroke cycle in the release phase, while the elite swimmers allocated only the 5.0% of the stroke cycle in this phase. Significant interaction trial × skill level (p=0.015) with large effect size ($\eta^2=0.247$) was found from the ANOVA. The elite swimmers spent significantly shorter relative time in the release phase compared to the sub-elite swimmers in all the 6 trials (p<0.01 for all 6 trials)

![Figure 4.8: Relative release duration across the 6 trials (** significant difference between groups, p<0.01). Error bars represent the standard deviation.](image)

<table>
<thead>
<tr>
<th></th>
<th>df</th>
<th>F-ratio</th>
<th>Significance (p)</th>
<th>Effect size (partial η²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial</td>
<td>2.257,</td>
<td>8.137</td>
<td>0.001</td>
<td>0.368</td>
</tr>
<tr>
<td></td>
<td>31.599</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skill level</td>
<td>1,14</td>
<td>14.373</td>
<td>0.002</td>
<td>0.507</td>
</tr>
<tr>
<td>Trial x skill level</td>
<td>2.257,</td>
<td>4.585</td>
<td>0.015</td>
<td>0.247</td>
</tr>
<tr>
<td></td>
<td>31.599</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.10: Results of the repeated measures ANOVA for relative release phase (df, degrees of freedom).

4.6.5. Recovery phase

Figure 4.9 shows the relative duration of the recovery phase expressed as the percentile of the duration of the stroke cycle. Table 4.11 illustrates the results from the statistical analysis. Significant main effect of Trial with large effect size (p=0.004, η²=0.310) was found from the ANOVA. The relative time spent in the recovery phase decreased by 4.7% in trial 7 in relation to trial 3 (p=0.011). Significant main effect of Skill level was found with large effect size (p=0.006, η²=0.425) as the elite group spent on average the 25.1% of the stroke cycle in the recovery whereas the sub-elite group spent the 26.6%. Finally, no significant interaction trial × skill level with medium effect size was found from the ANOVA (p=0.528 η²=0.047).
Figure 4.9: Relative recovery duration across the 6 trials. Error bars represent the standard deviation.

<table>
<thead>
<tr>
<th></th>
<th>df</th>
<th>F-ratio</th>
<th>Significance (p)</th>
<th>Effect size (partial $\eta^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial</td>
<td>2.296, 32.144</td>
<td>6.301</td>
<td>0.004</td>
<td>0.310</td>
</tr>
<tr>
<td>Skill level</td>
<td>1,14</td>
<td>10.327</td>
<td>0.006</td>
<td>0.425</td>
</tr>
<tr>
<td>Trial x skill level</td>
<td>2.296, 32.144</td>
<td>0.689</td>
<td>0.528</td>
<td>0.047</td>
</tr>
</tbody>
</table>

Table 4.11: Results of the repeated measures ANOVA for relative recovery phase (df, degrees of freedom).

4.7. Relative duration of propulsive and non-propulsive phases of the arms

4.7.1. Propulsive phase of the arms

Figure 4.10 shows the relative duration of the propulsive phase (pull and push) of the arms expressed as the percentile of the duration of the stroke cycle. The ANOVA results shown in
Table 4.12 revealed a significant main effect of Trial with large effect size \( (p=0.004, \eta^2=0.338) \). The relative duration of the propulsive phase increased significantly from trial 3 to trial 7 \( (p=0.031) \) by 3.7\%, before it decreased significantly by 2.4\% from trial 7 to trial 9 \( (p=0.012) \). Furthermore, the relative duration of the propulsive phase was significantly shorter in trial 11 compared to trials 5 \( (p=0.007) \), 7 \( (p<0.001) \) and 9 \( (p=0.011) \) with those changes corresponding to a reduction of 2.9\%, 3.6\% and 1.2\% respectively. Significant main effect of Skill level with large effect size \( (p=0.002, \eta^2=0.496) \) was also revealed from the statistical analysis as, across the 6 trials, elite group’s propulsive phase corresponded to the 44.4\% of the duration of the stroke cycle, whereas the relative percentage of the sub-elite group was 36.7\%.

In addition to those two significant main effects, significant interaction trial \( \times \) skill level with large effect size was found \( (p=0.047, \eta^2=0.145) \). In every trial, the elite swimmers spent significantly longer time in the propulsive phase compared to the sub-elite swimmers \( (p<0.01 \) for all the 6 trials).

![Figure 4.10: Relative duration of the propulsive phase of the elite and sub-elite group over the course of the 6 trials (**significant difference between groups \( p<0.01 \)). Error bars represent the standard deviation.](image)

82
<table>
<thead>
<tr>
<th></th>
<th>df</th>
<th>F-ratio</th>
<th>Significance (p)</th>
<th>Effect size (partial η²)</th>
</tr>
</thead>
</table>
| Trial          | 1.827,  
25.576 | 7.148   | 0.004            | 0.338                   |
| Skill level    | 1.14     | 13.756  | 0.002            | 0.496                   |
| Trial x skill level | 1.827,  
25.576 | 2.382   | 0.047            | 0.145                   |

Table 4.12: Results of the repeated measures ANOVA for relative duration of propulsive phase (df, degrees of freedom).

### 4.7.2. Non-propulsive phase of the arms

Figure 4.11 shows the relative duration of the non-propulsive phase (entry, release and recovery) of the arms expressed as the percentile of the duration of the stroke cycle. Table 4.13 displays the results from the statistical analysis. Significant main effect of Trial with large effect size (p=0.004, η²=0.346) was found. The relative duration of the non-propulsive phase decreased significantly from trial 3 to trial 7 (p=0.031) by 2.5%, whereas, the relative duration increased significantly by 1.7% from trial 7 to trial 9 (p=0.012). Significantly shorter relative durations of the non-propulsive phase were found in trials 5 by 2.0% (p=0.003), 7 by 2.6% (p<0.001) and 9 by 0.8% (p=0.011) in relation to trial 11. Significant main effect of Skill level with large effect size (p=0.002, η²=0.496) was also found. Across the 6 trials, the elite swimmers allocated significantly smaller relative percentile in the non-propulsive phase compared to the sub-elite swimmers (55.6% and 63.3% respectively). Moreover, significant interaction trial × skill level with large effect size was found (p=0.050, η²=0.139) as, in each one of the 6 trials, the sub-elite swimmers spent longer relative time in the non-propulsive phase in relation to the elite swimmers (p<0.01 for all the 6 trials).
Figure 4.11: Relative duration of the non-propulsive phase of the elite and sub-elite group over the course of the 6 trials (** significant difference between groups p<0.01). Error bars represent the standard deviation.

<table>
<thead>
<tr>
<th></th>
<th>df</th>
<th>F-ratio</th>
<th>Significance (p)</th>
<th>Effect size (partial η²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial</td>
<td>1.791,</td>
<td>7.402</td>
<td>0.004</td>
<td>0.346</td>
</tr>
<tr>
<td></td>
<td>25.077</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skill level</td>
<td>1.14</td>
<td>13.766</td>
<td>0.002</td>
<td>0.496</td>
</tr>
<tr>
<td>Trial x skill level</td>
<td>1.791,</td>
<td>2.268</td>
<td>0.050</td>
<td>0.139</td>
</tr>
<tr>
<td></td>
<td>25.077</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.13: Results of the repeated measures ANOVA for relative duration of non-propulsive phase (df, degrees of freedom).
4.8. Shoulder and hip roll

4.8.1. Shoulder roll

Figure 4.12 illustrates the maximum shoulder roll angles of the elite and sub-elite swimmers during the course of the 6 trials. In Table 4.14 the results from the statistical analysis are displayed. Significant main effect of Trial with large effect size was found ($p<0.001$, $\eta^2=0.423$) as the post-hoc analysis showed that maximum shoulder roll angle of the participants in trial 11 was greater than in trials 1 ($p=0.018$), 3 ($p=0.003$) and 5 ($p=0.006$) by 6.6%, 6.2% and 5.4% respectively. This main effect of trial can be mostly attributed to the changes observed in the sub-elite swimmers as these changes mask the fact that the shoulder roll of the elite swimmers did not change significantly across the trials. No significant main effect of Skill level with medium effect size was found ($p=0.338$, $\eta^2=0.066$). Similarly, there was no significant interaction trial $\times$ skill level ($p=0.458$) with the effect size found to be medium ($\eta^2=0.063$).

![Shoulder Roll Graph](image)

Figure 4.12: Shoulder roll of the elite and sub-elite group over the course of the 6 trials. Error bars represent the standard deviation.
<table>
<thead>
<tr>
<th></th>
<th>df</th>
<th>F-ratio</th>
<th>Significance (p)</th>
<th>Effect size (partial $\eta^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial</td>
<td>5, 70</td>
<td>10.248</td>
<td>&lt;0.001</td>
<td>0.423</td>
</tr>
<tr>
<td>Skill level</td>
<td>1,14</td>
<td>0.983</td>
<td>0.338</td>
<td>0.066</td>
</tr>
<tr>
<td>Trial x skill level</td>
<td>5, 70</td>
<td>0.944</td>
<td>0.458</td>
<td>0.063</td>
</tr>
</tbody>
</table>

Table 4.14: Results of the repeated measures ANOVA for shoulder roll (df, degrees of freedom).

4.8.2. Hip roll

Figure 4.13 shows the maximum hip roll angles of the elite and sub-elite swimmers over the course of the 6 trials. As it can be seen in Table 4.15 which presents the results of the statistical analysis, significant main effects of Trial (p<0.001) and Skill level (p=0.050) were found with large effect sizes ($\eta^2=0.529$ and $\eta^2=0.245$ respectively). With respect to main effect of Trial, which, similarly to shoulder roll, was found due to the changes observed in the sub-elite group, the post-hoc analysis revealed that the swimmers increased their hip roll angle in trials 7, 9 and 11 by 7.4% (p=0.034), 9.2% (p=0.032), and 12.3% (p=0.002) respectively in relation to trial 1. Moreover, swimmers’ hip roll angles were greater by 6.4% in trial 7 (p=0.004), 8.2% in trial 9 (p=0.003) and 11.2% in trial 11 (p=0.001) compared to trial 3. In addition, the hip roll angle of the swimmers in trial 11 was significantly larger by 8.3% (p=0.015) and 4.6% (p=0.048) compared to trials 5 and 7 respectively. Regarding the main effect of Skill level, it was found that, across the 6 trials, the average hip roll angle achieved by the sub-elite swimmers (38.1 degrees) was significantly greater than the one achieved by the elite swimmers (30.7 degrees). Furthermore, significant interaction trial $\times$ skill level with large effect size (p<0.001, $\eta^2=0.278$) was revealed from the statistical analysis with the sub-elite swimmers displaying significantly greater hip roll angles than the elite swimmers in trials 9 and 11 (both p<0.05).
Figure 4.13: Hip roll of the elite and sub-elitie group over the course of the 6 trials (* significant difference between groups p<0.05). Error bars represent the standard deviation.

<table>
<thead>
<tr>
<th></th>
<th>df</th>
<th>F-ratio</th>
<th>Significance (p)</th>
<th>Effect size (partial η²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial</td>
<td>5, 70</td>
<td>15.723</td>
<td>&lt;0.001</td>
<td>0.529</td>
</tr>
<tr>
<td>Skill level</td>
<td>1,14</td>
<td>4.533</td>
<td>0.050</td>
<td>0.245</td>
</tr>
<tr>
<td>Trial x skill level</td>
<td>5, 70</td>
<td>5.378</td>
<td>&lt;0.001</td>
<td>0.278</td>
</tr>
</tbody>
</table>

Table 4.15: Results of the repeated measures ANOVA for hip roll (df, degrees of freedom).
4.9. Intracycle Velocity Variations

4.9.1. Horizontal axis

Figure 4.14 presents the maximum (Vmaxx) and minimum (Vminx) swimming velocities in the swimming direction along with the intracycle velocity variation (IVVx) in the same direction. Significant main effects of Trial with large effect sizes were found for Vmaxx (p<0.001, $\eta^2=0.603$), Vminx (p<0.001, $\eta^2=0.367$) and IVVx (p<0.001, $\eta^2=0.345$) as shown in Table 4.16 where the ANOVA results are presented. With respect to Vmaxx, the swimmers produced significantly higher Vmaxx in trial 1 compared to trials 5 (p=0.033), 7 (p=0.023), 9 (p=0.032) and 11 (p=0.041) as the Vmaxx dropped by 3.5%, 5.5%, 6.5% and 7.0% respectively. Similarly, Vmaxx decreased by 1.5% in trial 5 (p=0.031), 3.6% in trial 7 (p=0.01), 4.6% in trial 9 (p=0.002) and 5.1% in trial 11 (p<0.001) in relation to trial 3. Significant decrease in Vmaxx was also found from trial 5 to trials 7 (p=0.029), 9 (p=0.024) and 11 (p=0.016) as the Vmaxx dropped by 2.1%, 3.1% and 3.6% respectively. Finally, the Vmaxx reduced by 1.6% from trial 7 to trial 11 (p=0.042). Regarding the main effect of Trial in Vminx, it was found that the Vminx in trial 11 was significantly lower compared to trial 1 (p=0.027), trial 5 (p=0.050), trial 7 (p=0.001) and trial 9 (p=0.029) as the magnitude of the reduction in Vminx corresponded to 6.7%, 4.1%, 3.4% and 2.8% respectively. As far as the main effect of Trial in IVVx is concerned, there was a significant decrease in IVVx values in trials 7 and 9 in relation to trial 1 (p<0.033-10.2% and p=0.035-14.2% respectively), trial 3 (p=0.031-10.2% and p=0.044-14.2% respectively) and trial 5 (p=0.021-6.4% and p=0.050-10.6% respectively).

Significant main effect of Skill level with large effect sizes were found for Vmaxx (p<0.001, $\eta^2=0.759$), Vminx (p<0.005, $\eta^2=0.440$) and IVVx (p<0.001, $\eta^2=0.869$). Over the course of the
6 trials, the elite swimmers achieved significantly higher Vmaxx, Vminx and IVVx than the sub-elite ones with those differences corresponding to 14.0%, 6.4% and 4.2% respectively.

Significant interactions trial × skill level with large effect sizes were also found for Vmaxx (p<0.001, $\eta^2=0.289$) and Vminx (p=0.028, $\eta^2=0.161$). The elite group displayed greater Vmaxx (p<0.001 for all 6 trials) and Vminx (p<0.05 in trials 1, 3, 5 and 9; p<0.01 in trials 7 and 11) compared to the sub-elite group. The interaction trial × skill level for IVVx was not significant with medium effect size (p=0.096, $\eta^2=0.123$).

Figure 4.15 shows the relative maximum (Vmaxx%) and minimum (Vminx%) velocities along with the relative intracycle velocity variation (IVVx%) in the swimming direction, all expressed as a percentage of the mean velocity (Vmeanx) in the swimming direction. Table 4.16 presents the results from the statistical analysis for the aforementioned parameters. Significant main effect of Trial with large effect size was found for Vmaxx% (p<0.001, $\eta^2=0.297$) as Vmaxx% in trial 9 was significantly smaller than in trial 1 by 2.1%. In contrast, no significant main effect of Trial with medium effect sizes were found for Vminx% (p=0.131, $\eta^2=0.112$) and IVVx% (p=0.316, $\eta^2=0.072$).

The main effects of Skill level were found to be significant with large effect sizes for Vmaxx% (p<0.001, $\eta^2=0.807$), Vminx% (p<0.001, $\eta^2=0.712$) and IVVx% (p<0.001, $\eta^2=0.822$). The elite swimmers, on average, produced greater Vmaxx% and IVVx% values (117.1% and 31.1% respectively) than the sub-elite ones (112.8% and 23.8% respectively), while on the contrary, the sub-elite swimmers displayed greater Vminx% values than the elite ones (89.0% and 86.1% respectively).

No significant interactions trial × skill level were found for any of Vmaxx% (p=0.269), Vminx% (p=0.596) or IVVx% (p=0.360) with the effect sizes being $\eta^2=0.086$ (medium), $\eta^2=0.050$ (small) and $\eta^2=0.074$ (medium) respectively.

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Figure 4.14: Maximum velocity (Vmax), minimum velocity (Vmin) and intracycle velocity variation (IVVx) in the horizontal axis across the 6 trials (*significant difference between groups p<0.05, ** significant difference between groups p<0.01, *** significant difference between groups p<0.001). Error bars represent the standard deviation.

Figure 4.15: Relative maximum velocity (Vmax%), relative minimum velocity (Vmin%) and relative intracycle velocity variation (IVVx%) in the horizontal axis across the 6 trials. Error bars represent the standard deviation.
<table>
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<tr>
<th>Variable</th>
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Table 4.16: Results of the repeated measures ANOVA for maximum velocity (Vmaxx), minimum velocity (Vminx), intracycle velocity variation (IVVx), relative maximum velocity (Vmaxx%), relative minimum velocity (Vminx%) and relative intracycle velocity variation (IVVx%) in the horizontal axis (df, degrees of freedom).
4.9.2. Vertical axis

The maximum (Vmaxy), minimum (Vminy) and intracycle (IVVy) velocities in the vertical axis are presented in Figure 4.16. Table 4.17 illustrates the ANOVA results for the aforementioned variables. No significant main effect of Trial with medium effect sizes were found for Vmaxy and IVVy (both \( p=0.174, \eta^2=0.102 \)). The Vminy was close to 0 for all the swimmers due to the fact that the velocity in vertical axis changed from one direction to the other (i.e. transition from positive to negative values) during the stroke cycle. For that reason, no statistical analysis was conducted for this variable or its relative variable (Vminy%).

The main effects of Skill level were found to be significant with large effect sizes for Vmaxy and IVVy (both \( p=0.005, \eta^2=0.436 \)). It was found that the elite swimmers produced greater Vmaxy and IVVy than the sub-elite swimmers with the differences being 12.8% for both variables.

No significant interactions trial × skill level with small effect sizes were found for Vmaxy and IVVy (both \( p=0.738, \eta^2=0.038 \)).

Figure 4.17 presents the relative maximum (Vmaxy%), minimum (Vminy%) and intracycle (IVVy%) velocities in the vertical axis expressed as a percentage of the mean velocity in the swimming direction. The ANOVA results for Vmaxy% and IVVy% are presented in Table 4.17. No significant main effect of Trial with small effect sizes were found for Vmaxy% and IVVy% (\( p=0.588, \eta^2=0.051 \) for both variables).

No significant main effects of Skill level with small effect sizes were found for Vmaxy% (\( p=0.589, \eta^2=0.021 \)) or IVVy% (\( p=0.548, \eta^2=0.026 \)).
No significant interactions with small effect sizes were found for $V_{\text{maxy}}\%$ ($p=0.529$, $\eta^2=0.056$) and $IV_{Vy}\%$ ($p=0.536$, $\eta^2=0.056$).

![Figure 4.16](image1.png)

**Figure 4.16**: Maximum velocity ($V_{\text{maxy}}$), minimum velocity ($V_{\text{miny}}$) and intracycle velocity variation ($IV_{Vy}$) in the vertical axis across the 6 trials. Error bars represent the standard deviation.

![Figure 4.17](image2.png)

**Figure 4.17**: Relative maximum velocity ($V_{\text{maxy}}\%$), relative minimum velocity ($V_{\text{miny}}\%$) and relative intracycle velocity variation ($IV_{Vy}\%$) in the vertical axis across the 6 trials ($**$ significant difference between groups $p<0.01$, $***$ significant difference between groups $p<0.001$). Error bars represent the standard deviation.
<table>
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<tr>
<th>Variable</th>
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Table 4.17: Results of the repeated measures ANOVA for maximum velocity (Vmaxy), minimum velocity (Vminy), intracycle velocity variation (IVVy), relative maximum velocity (Vmaxy%), relative minimum velocity (Vminy%) and relative intracycle velocity variation (IVVy%) in the vertical axis (df, degrees of freedom).
4.9.3. Lateral axis

The maximum velocity (Vmaxz), minimum velocity (Vminz) and intracycle velocity (IVVz) in the lateral axis are illustrated in Figure 4.18, while Table 4.18 presents the results of the statistical analysis for those variables. No significant main effects of Trial with small effect sizes were found for Vmaxz and IVVz (p=0.893, $\eta^2=0.023$ for both variables). No statistical analysis was conducted for Vminz or Vminz% as, similar to Vminy, the velocity in lateral axis changed direction throughout the stroke cycle and therefore the Vminz values were close to 0 for all the swimmers.

No significant main effects of Skill level with medium effect sizes were found for Vmaxz and IVVz (both p=0.302, $\eta^2=0.076$).

Finally, the interactions trial × skill level were found to be non-significant for Vmaxz and IVVz (both p=0.839) with small effect sizes (both $\eta^2=0.029$).

The relative maximum velocity (Vmaxz%) and relative intracycle velocity (IVVz%) are shown in Figure 4.19. The results of the ANOVA are presented in Table 4.18. Non-significant main effects of Trial with small effect sizes were found for Vmaxz% (p=0.880, $\eta^2=0.025$) and IVVz% (p=0.888, $\eta^2=0.024$).

Significant main effects of Skill level with large effect sizes were revealed for Vmaxz% (p=0.036, $\eta^2=0.277$) and IVVz% (p=0.039, $\eta^2=0.270$). The sub-elite group achieved significantly greater Vmaxz% and IVVz% values than the elite group with sub-elite group’s values being, on average, larger by 7.1% and 7.1% respectively.
No significant interactions with small effect sizes were found for Vmaxz% and IVVz% (p=0.972, $\eta^2=0.012$ for both variables).

Figure 4.18: Maximum velocity (Vmaxz), minimum velocity (Vminz) and intracycle velocity variation (IVVz) in the lateral axis across the 6 trials. Error bars represent the standard deviation.

Figure 4.19: Relative maximum velocity (Vmaxz%), relative minimum velocity (Vminz%) and relative intracycle velocity variation (IVVz%) in the lateral axis across the 6 trials (**significant difference between groups p<0.01, *** p<0.001). Error bars represent the standard deviation.
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<th>Significance (p)</th>
<th>Effect size (partial $\eta^2$)</th>
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Table 4.18: Results of the repeated measures ANOVA for maximum velocity (Vmaxz), minimum velocity (Vminz), intracycle velocity variation (IVVz), relative maximum velocity (Vmaxz%), relative minimum velocity (Vminz%) and relative intracycle velocity variation (IVVz%) in the lateral axis (df, degrees of freedom).
5. Discussion

The purpose of the present study was to investigate the adaptations in the kinematic characteristics of male sprint swimmers during a maximal intermittent training set. Furthermore, the present study sought to examine whether there are kinematic characteristics accountable for the different skill level/performance between elite and sub-elite sprint swimmers and also to explore whether elite and sub-elite swimmers are affected differently by fatigue depending on their skill level. The hypotheses of the present study were accepted as the main findings were that the performance-related kinematic characteristics of elite and sub-elite swimmers changed significantly during the course of the testing protocol. Moreover, significant differences in performance-related kinematic variables were found between the elite and sub-elite group. Finally, during the course of the training set, the elite swimmers maintained better kinematic parameters associated with performance.

In the previous chapter, the results of the kinematic variables were presented with respect to the effect of skill level, effect of trial (fatigue) and the interaction between skill level and trial. In this chapter, the difference and similarities in the dependent variables at different skill levels and across the trials are discussed.

5.1. V, SL and SF

5.1.1. Effect of fatigue

As expected, participants’ V decreased significantly from trial 1 to trial 11 indicating that the testing protocol produced considerable levels of fatigue to all of the participants and resulted in a decrease in swimmers’ power output generating capacity. In accordance with these findings, decreases in V have been found in studies in which the effect of fatigue on kinematic
characteristics during maximal trials in swimming was investigated (Au jouan et al., 2006; Tella et al., 2008).

V decreased significantly by 5.3% from trial 1 to trial 11 as participants’ V dropped from 1.71 m·s\(^{-1}\) to 1.62 m·s\(^{-1}\). This finding is in-line with the results from studies conducted in front crawl in which significant decreases in V were reported at the end of 100- and 200-m races or race simulations (Craig et al., 1985; Figueiredo et al., 2012a; Ikuta et al., 2012; Psycharakis et al., 2010) and at the end of series of maximal trials (Au jouan et al., 2006; Tella et al., 2008). Au jouan et al. (2006) tested male swimmers over the course of 4 maximal 50-m trials separated by 10 seconds rest simulating a 200-m race. The researchers reported that V reduced by 16.3% from trial 1 to trial 4 (from 1.29 m·s\(^{-1}\) to 1.08 m·s\(^{-1}\) respectively). This percentile is considerably greater to the one found in the present study (5.3%). This difference may be attributed to the quicker development of fatigue in the former study due to the shorter rest between the trials (10 seconds) compared to the present study (approximately 40 seconds). Moreover, the skill level of the participants and/or the recording device used in the former study may have played important roles on this difference in the magnitude of V reduction. There was no specific information about participants’ skill level reported by the researchers, and also, as the authors speculated, swimmers’ V was affected by the attached EMG system resulting in an increase in resistive forces and therefore limiting the performance. Tella et al. (2008) investigated the changes in kinematic variables between 2 maximal 25-m trials, one trial before and one 10 seconds after a fatiguing 75-m bout at maximal intensity. In accordance with Au jouan et al. (2006), Tella et al. (2008) also reported a decrease of 16.3% (from 1.60 m·s\(^{-1}\) to 1.34 m·s\(^{-1}\) ) in V in the fatiguing condition. The difference in the findings between the study of Tella et al. (2008) and the present study with respect to the magnitude of V reduction can be explained by the different protocols (considerably shorter rest was given to the swimmers between trials in the former study) and/or the skill level of the participants based on the V values achieved from the swimmers in each study (i.e. considerably higher V values
were observed in the present study compared to those in the study of Tella et al., 2008). Indeed, it has been suggested that more skilled swimmers maintain their V better under fatiguing conditions compared to the less skilled swimmers (Chollet et al., 1997; Seifert et al., 2007a). This issue is further explored in the next section (5.1.2).

In the present study, swimmers’ reduction in V during the course of the trials was due to the decrease in SL as the SF remained unchanged. The SL reduced significantly by 4.0% in trial 7 (2.16 m) and by 4.9% in trial 11 (2.14 m) in relation to trial 1 (2.25 m). Regarding the effect of fatigue on interrelationship between SL and SF, the findings of the present study are not in-line with other studies, although previous results have been equivocal. Some studies have reported reductions in SL and SF as a consequence of fatigue (Alberty et al., 2005), whereas others have observed a constant SL along with reductions in SF (Aujouannet et al., 2006; Toussaint et al., 2006). Furthermore, a reduction in SL along with an increase in SF has also been reported (Alberty et al., 2009). In the present study, the participants maintained their SL until trial 7 in which the statistical analysis showed a significant decrease in this variable. It can therefore be hypothesised, that the higher volume (600-m) and longer duration (5.5 minutes of total effort) of the protocol employed in the present study accounted for the changes in SL, as the previous studies tested the swimmers in 100-200 m race simulations (Alberty et al., 2005; Toussaint et al., 2006), during 200-m of intermittent maximal exercise (Aujouannet et al., 2006), or during short duration (68 seconds) constant-speed maximal efforts (Alberty et al., 2009). The reductions in SL due to fatigue have been associated to the development of local muscular fatigue in muscles responsible for generating propulsion (Keskinen and Komi, 1993; Stirn et al., 2011). Indeed, Figueiredo et al. (2013b) using EMG, reported higher activation of flexor carpi radialis, biceps brachii, triceps brachii, pectoralis major and upper trapezius during a maximal 200-m trial in front crawl. Those muscles play an important role in front crawl (Stirn et al., 2011) and their higher activation indicates the need to recruit additional muscle fibres in response to the development of fatigue.
5.1.2. Effect of skill level

Regarding the effect of skill level on V, SL and SF, the results of the present study suggest that the elite swimmers achieved significantly higher average V and SL values (1.74 m·s⁻¹ and 2.30 m respectively) compared to the sub-elite ones (1.59 m·s⁻¹ and 2.09 m respectively) throughout the course of the trials, while no differences were found in SF between the groups (44.7 cycles·min⁻¹ and 45.7 cycles·min⁻¹ for the elite and sub-elite group respectively). The V, SL and SF values per group reported in the present study are comparable to those reported by Seifert et al. (2007a) for groups of swimmers of the same skill level as the present study (personal best times corresponding to 90% and 80% of the World Record) during the course of a maximal 100-m trial. The values reported by Seifert et al. (2007a) for the 2nd lap of the 100-m trial (relevant to the imposed pace in the present study) were V of 1.79 m·s⁻¹ and 1.63 m·s⁻¹, SL of 2.17 m and 1.93 m, and SF of 44.4 cycles·min⁻¹ and 45.0 cycles·min⁻¹ for the elite and sub-elite group respectively.

The difference in SL observed between the 2 groups of the present study can be partially attributed to the fact that the elite swimmers were 3.3% taller than the sub-elite ones, as it has been suggested that the body height positively influences SL (Arellano et al., 1994; Kennedy et al., 1990; Pelayo et al., 1996). Other anthropometric parameters, such as arm and leg lengths, arm span, axilla, hand and foot cross sectional areas and leg frontal area, have been known to influence SL (Grimston and Hay, 1986; Seifert et al., 2007a), however these parameters were not tested in the present study. These findings of the present study are in line with other studies in which more skilled swimmers were characterised by greater V, longer SL and equal SF compared to the less skilled swimmers (Chollet et al., 1997; Seifert et al., 2007a). Indeed, SL has been suggested to be the best predictor of swimming performance (Costill et al., 1985).

In the present study the elite group produced significantly higher V and longer SL than the sub-elite group (p<0.01) in each one of the analysed trials. The elite group also managed to
maintain more constant V and SL throughout the course of the trials compared to the sub-elite group, as in the former group V and SL dropped by 2.8% and 1.7% respectively between trials 1 and 11, whereas in the sub-elite group larger reductions of 8.4% and 4.1% were observed in V and SL respectively. These findings are in line with the existing literature, as it is well documented that highly skilled swimmers are characterised by a more constant V and SL throughout strenuous swimming trials (Chollet et al., 1997; Seifert et al., 2007a).

To summarise, in the present study, as fatigue developed during the testing protocol, the participants reduced their V by displaying shorter SL and maintaining their SF. This finding contradicts the findings of other studies. A possible explanation could be the longer and more demanding protocol of the present study. In line with the literature, the elite group displayed significantly higher V and longer SL in each trial compared to the sub-elite group. Also, in accordance with other studies, the former group managed to maintain better their V and SL (as reflected by the lower % reduction) with the development of fatigue compared to the latter group. The data of the present study regarding V, SL and SF contribute to the existing knowledge in the topic by providing comparable information on high-calibre swimmers during a long intermittent maximal set.

5.2. SI

5.2.1. Effect of fatigue

In the previous section the impairment in V and SL as a result of fatigue was discussed. Since SI is the product of SL and V, it is unsurprising that higher SI values were observed in trial 1 (3.82 m$^2$-cycles$^{-1}$-min$^{-1}$) compared to trial 7 (3.54 m$^2$-cycles$^{-1}$-min$^{-1}$), trial 9 (3.56 m$^2$-cycles$^{-1}$-min$^{-1}$) and trial 11 (3.47 m$^2$-cycles$^{-1}$-min$^{-1}$) corresponding to a reduction of 9.2% between trial 1 and trial 11. Longo et al. (2008) reported that SI decreased by 23.2% throughout a 400-m
maximal trial from 3.92 m²-cycles⁻¹-min⁻¹ in the 1st 100-m lap to 3.01 m²-cycles⁻¹-min⁻¹ in the 4th 100-m lap. On the contrary, during incremental protocols in front crawl, SI has been found to remain unchanged (Komar et al., 2012; Seifert et al., 2010a). The findings of the present study with respect to changes in SI due to fatigue are not directly comparable with the findings of Longo et al. (2008), Komar et al. (2012) and Seifert et al. (2010a) due to differences in the testing protocols which were employed.

5.2.2. Effect of skill level

In-line with other studies (Costill et al., 1985; Sánchez and Arellano, 2002), the elite group in the present study was superior to the sub-elite with respect to SI across the trials. The former group achieved on average SI values of 3.94 m²-cycles⁻¹-min⁻¹ while the latter 3.33 m²-cycles⁻¹-min⁻¹ across the 6 analysed trials. The SI values observed in the present study are similar to those reported by Sánchez and Arellano (2002) for international level (3.85 m²-cycles⁻¹-min⁻¹) and national level (3.25 m²-cycles⁻¹-min⁻¹) swimmers from competition analysis during a 100-m front crawl. In the present study, the differences in SI values between the 2 groups could be simply explained by the differences in V and SL as discussed in the previous section (5.1.2).

Similarly to V and SL, the elite group not only displayed significantly higher SI values compared to the sub-elite group in each one of the 6 trials that were analysed (p<0.05 for trial 1 and p<0.01 for the rest of the trials), but also maintained more constant SI throughout the course of the trials (reductions of 4.0% and 14.9% for the elite and sub-elite group respectively between trial 1 and trial 11). Since SI has been suggested to have a strong negative relationship with the energy expenditure (Costill et al., 1985; ), the better maintenance of SI achieved by the elite group highlights the superiority of the elite swimmers in energetic capacity in order to delay the development of local muscular fatigue (Costa et al., 2012).
5.3. Stroke phase durations

5.3.1. Effect of fatigue

In the present study, the development of fatigue affected the temporal characteristics of swimmers’ technique. Despite the relative duration of entry phase which remained unchanged throughout the course of the testing protocol, the duration of the pull and push phases increased in the middle stage of the protocol (trials 5 and 7) before they decreased at the last stage (trials 9 and 11), conversely, the duration of the release and recovery phases decreased in the middle and increased at the last stage. Similar to the pull and push phases, the relative duration of the propulsive phase (pull and push) increased in the middle stage of the protocol before it decreased at the last stage. Finally, the changes observed in the relative duration of the non-propulsive phase (entry, release, recovery) were opposite to those reported for the propulsive phase. It should be noted that, in the literature, there is a common misinterpretation with regards to the meaning of the propulsive and non-propulsive phase duration of the stroke. In particular, clarification is required in relation to the period over which the arms apply propulsive forces at pull and push phases; these forces are not necessarily translated into propulsion for the whole body as it is commonly perceived. As speculated in literature review (section 2.3.2.3), the propulsive forces are dependent upon a number of parameters.

Alberty et al. (2005) investigated the effect of fatigue on the relative duration of the stroke phases during a maximal 200-m trial and in 2 trials of 25-m at maximal intensity performed before (rested condition) and after (fatigued condition) the 200-m trial. In general agreement with the findings of the present study, Alberty et al. (2005) reported that the relative duration of the entry phase was not affected by the development of fatigue both during the course of the 200-m trial (ranged 33.2-34.7%) and between the 25-m trials (30.8% and 28.8% for the 1st and the 2nd 25-m trial respectively). The same researchers reported a significant increase in the
relative duration of the pull phase throughout the 200-m trial (from 16.2% in the 1st 50-m lap to 18.9% in the 4th 50-m lap) and between the 25-m trials (17.9% and 20.7% in the 1st and 2nd 25-m respectively). The latter finding is in accordance with the present results, with the exception of a significant decrease in trial 11 in relation to trial 7 that was observed in the present study. This decrease may be attributed to the volume/duration of the protocol in the present study, meaning that due to the greater fatigue at the last stage of the protocol, the swimmers did not manage to change their temporal stroking characteristics in order to allocate longer time in this phase. Furthermore, Albery et al. (2005) found that the relative duration of the push phase increased in the second half of the 200-m trial (23.6%) compared to the first half (22.2%), whereas the push duration did not change between the 25-m trials. This contradicts the present findings with respect to the relative duration of the push phase, as this variable decreased at the last stage of the testing protocol compared to the middle stage. However, it should be noted that the push phase in the present study was defined in a different manner to the one used by Albery et al. (2005). In fact, the push phase as defined in the latter study corresponds to the sum of push and release phase in the present study as explained in section 2.3.2.4 of the literature review. Considering this difference, it can be stated that the sum of the relative duration of push and release phases increased throughout the course of the trials (from 26.5% in trial 1 to 27.4% in trial 11) and therefore the findings are in line with those of Albery et al. (2005). Regarding the relative duration of the recovery phase, Albery et al. (2005) reported a significant decrease from the 1st (27.1%) and 2nd lap (25.8%) to the 3rd (24.8%) and 4th lap (24.1%) of the 200-m trial. Similar adjustments were also reported between the 25-m trials as the recovery duration reduced from 25.6% to 24.4%. Complementarily, Albery et al. (2005) reported an increase of the propulsive phase (pull and push) during both the 200-m trial (38.2% in the 1st 50-m lap to 42.3% in the 4th 50-m lap) and between the 25-m trials (43.6% in the 1st 25-m to 47.1 in the 2nd 25-m trial). Albery et al. (2005) stated that the increases in the relative duration of the propulsive phase observed in their study can be attributed to the fact that the SF of the participants decreased significantly and therefore the
duration of the stroke cycle increased. Indeed, SF has been suggested to be the major
determinant of temporal characteristics in swimming affecting the durations of the stroke
phases (Alberty et al., 2008; Seifert et al., 2007b) and when a constant SF is imposed no
differences in the temporal characteristics of the stroke cycle are observed (Alberty et al.,
2008). In the present study, SF remained unchanged throughout the testing protocol.
Swimmers when fatigued try to increase their SF to compensate for the reduction in their SL
(Aberty et al., 2009) in order to maintain their V. In the present study, the swimmers failed to
increase their SF which indicates the failure in neural activation due to fatigue as suggested by
Keskinen and Komi (1993). To summarise, the changes in temporal characteristics of the
stroke reported by Alberty et al. (2005) are in absolute agreement with those of the present
study until trial 7. At the last stage of the present testing protocol (trials 9 and 11), the
participants displayed different adjustments in their technique compared to the middle stage
due to the development of peripheral and central fatigue.

5.3.2. Effect of skill level

Regarding the differences between the elite and sub-elite group with respect to the relative
duration of the stroke phases across the 6 trials, the latter group allocated significantly longer
relative time in the entry, release and recovery phases (27.9%, 8.8% and 26.7% respectively)
compared to the former group (25.5%, 5.0% and 25.1% respectively). On the contrary, the
elite swimmers spent significantly longer time in pull and push phases (22.4% and 22.0%
respectively) compared to the sub-elite ones (18.3% in both phases). Consequently, it was
found that, across the course of the trials, the elite swimmers spent significantly longer time
in the propulsive phases of the arms compared to the sub-elite ones (44.4% and 36.7%
respectively). These results are in-line with the findings of Chollet et al. (2000), who reported
that more skilled swimmers spent shorter relative time in the entry phase and longer relative
time in pull and push phases compared to less skilled ones at velocities corresponding to 50-
m and 100-m races. Since no differences in SF were observed between the groups in the
present study, and therefore the duration of the stroke cycles were similar in the elite and sub-
elite groups, the superiority of the former group with respect to the better efficiency (higher 
SL and SI values) that was observed, can be, at least, partially attributed to the fact that the 
elite group increased the relative time for propelling their body forward compared to the sub-
elite one. However, as stated by Schnitzler et al. (2011), the aforementioned characteristic of 
the more skilled swimmers to devote longer time in propulsive phases may be difficult to 
interpret as other factors may interfere. Indeed, it has been suggested that, apart from the 
relative duration of the stroke cycle over which the propulsive forces are applied, the efficiency 
of the swimmers depends on the ability to produce high propulsive impulses (Sanders, 2002), 
which are dependent on factors such as hand direction, hand path, hand velocity and angle of 
the hand during the pull and push phases (Toussaint and Beek, 1992) and anthropology 
(Seifert et al., 2004). Furthermore, increases in relative duration of the propulsive phases have 
been linked with decreases in hand velocity (Alberty et al., 2005) and there is a positive 
relationship between hand velocity and generated propulsive forces (Toussaint and Beek, 
1992). For example, in the present study, although the sub-elite swimmers increased the 
relative time devoted to the propulsive phases of the arms in trials 5 and 7 in relation to trials 
1 and 3, this temporal adjustment was ineffective considering that this adjustment was 
followed by reductions in SL and V. Such phenomena were not observed in the elite 
swimmers’ group. These ineffective temporal adjustments of the sub-elite swimmers are 
进一步 supported by the findings of Seifert et al. (2007a) according to which, although sub-
elite swimmers increased the time spent in propulsive phase, the SL continued to decrease 
during a maximal 100-m trial. Finally, it should be stated that the discussion above regarding 
the relative duration of the propulsive phases is based on the assumption that the propulsion 
from the leg kicking action did not differ between the groups. Further research is recommended 
to examine the durations of stroke phases in relation to hand kinematics within the stroke 
phases in order to advance the understanding regarding the differences accountable for the 
skill level.
The elite swimmers in the present study maintained better the relative duration of the propulsive phase compared to the sub-elite ones. Indeed, the elite swimmers increased the relative duration of the arms’ propulsive phases in the middle stage (trials 5 and 7) and last stage (trials 9 and 11) compared to the first stage (trials 1 and 3), while on the contrary, the sub-elite swimmers displayed shorter relative duration of the propulsive phase in the last stage compared to the first one. This finding is further supported by Pelayo et al. (2007) who stated that less expert swimmers are not able to increase the duration of the propulsive forces of the arms in relation to expert swimmers during exhaustive swimming exercise. This is explained by the fact that less skilled swimmers are characterised by lower adaptability in terms of their temporal stroke organisation at a given task in relation to highly skilled swimmers (Schnitzler et al., 2010).

5.4. Shoulder and hip roll

5.4.1. Effect of fatigue

In the present study, concomitant with the development of fatigue, the magnitude of the shoulder roll gradually increased throughout the trials reaching statistically significant levels in trial 11 (54.7 degrees) compared to trials 1 (51.3 degrees), 3 (51.5 degrees) and 5 (51.9 degrees). Similar adjustments were observed with respect to the hip roll angle, as the swimmers rolled their hips to a greater magnitude as the fatigue protocol progressed. Indeed, significant increases were found in trials 7 (35.0 degrees), 9 (35.6 degrees) and 11 (36.6 degrees) in relation to trials 1 (32.6 degrees) and 3 (32.9 degrees). As speculated in the results (sections 4.8.1 and 4.8.2), these changes in the shoulder and hip roll magnitudes were due to the changes observed in the sub-elite group as opposed to elite group in which the shoulder and hip roll magnitudes did not change significantly across the course of the trials. This difference between elite and sub-elite swimmers can be partially attributed to the changes in
V between the groups as the protocol progressed (i.e. larger decreases in V were observed in sub-elite group). Indeed, Psycharakis and Sanders (2008) reported that the total hip roll angle increased from 44.5 degrees in the first 50-m lap to 54.7 degrees in the last lap due to fatigue (as indicated by reduction in V) during a maximal 200-m trial. Further, Yanai (2003), regardless any effect of fatigue, reported a negative relationship between V and hip roll angle. In opposition to the findings of the present study, Moreover, Figueiredo et al. (2013b) reported that the greatest shoulder roll angle during a maximal 200-m trial occurred in the 3rd 50-m lap in which the lowest V values were observed. In the present study, the relationships between shoulder roll-V and hip roll-V were examined post analysis and no statistically significant correlations were revealed (-0.30 ≤ r ≥ 0.13, p>0.05 and -0.32 ≤ r ≥ -0.13, p>0.05 respectively). The results of the present study suggest that the sub-elite swimmers rolled their shoulders and hips more as they fatigued. This observation can be attributed to the fact that the sub-elite swimmers, as a response to fatigue, rolled their shoulders more aiming for higher muscle activation of their upper body during the pull phase (Figueiredo et al., 2013b). Complementarily, simultaneously with the increase in the shoulder roll, the sub-elite swimmers rolled their hips more in order to avoid increases in resistive forces, as large differences in the magnitude between shoulder and hip roll have been linked with increase in the frontal surface area of the swimmers (Psycharakis and Sanders, 2008). Moreover, the increase in hip roll can be explained by the impairment in leg kicking actions due to the development of fatigue in lower limbs. As it has been suggested that leg kick stabilises the rotation of the body (Deschodt et al., 1999), further investigation of fatigue-induced changes in shoulder and hip roll changes in relation to leg kick would improve the understanding regarding the relationship between body roll and leg kick.

5.4.2. Effect of skill level

Regarding the effect of skill level on the shoulder and hip roll magnitudes, the present study found that sub-elite swimmers rolled their hips to a greater angle (38.1 degrees) across the 6
trials compared to the elite swimmers (30.7 degrees), whereas no statistically significant
differences in the shoulder roll angles were observed between the 2 groups (58.0 and 51.0 for
sub-elite and elite group respectively). In line with the findings of the present study, Cappaert
et al. (1995) reported that the sub-elite swimmers rolled their hips significantly more than the
elite ones during a 100-m race, while on the contrary, no differences were observed in the
shoulder roll angles between elite and sub-elite swimmers. However, Cappaert et al. (1995)
reported smaller shoulder (34.4 degrees 35.4 for elite and sub-elite swimmers respectively)
and hip roll (8.3 degrees and 17.8 degrees for elite and sub-elite swimmers respectively)
magnitudes compared to the present study. This difference can be attributed to the higher V
achieved in the former study (2.01 m·s⁻¹ and 1.87 m·s⁻¹ for elite and sub-elite swimmers
respectively), as V has been negatively associated with shoulder and hip roll angles (Yanai,
that the faster swimmers were characterised by significantly smaller shoulder roll angles
during a 200-m race simulation. In the present study, although on average the sub-elite
swimmers rolled their shoulders more than the elite ones, the difference did not reach statistical
significance, however, a medium effect size was observed. It can therefore be concluded that,
at a given intensity and regardless of the V achieved, less skilled swimmers tend to roll their
shoulders and hips more than highly skilled swimmers. Although the magnitude of the
shoulder and hip roll has been associated with reduced resistive forces applied on the
swimmer’s body (Castro et al., 2003), it has been suggested that the temporal characteristics
of the roll should be taken into consideration, as it has been observed that less skilled
swimmers rolled their shoulders and hips to the opposite direction and therefore peak shoulder
and hip roll angles might occur at different times, which causes increases in resistance
(Cappaert et al., 1995). Complementarily, the fact that the elite swimmers achieved higher V
concomitant with smaller hip roll angle may be due to the contributions of the leg actions
inhibiting the swimmers to roll, rather keeping them more balanced and stabilised in the water
at high intensities. However, Psycharakis and Sanders (2008) reported that the temporal
characteristics of the shoulder and hip roll are highly individual, are not affected by the
development of fatigue and are not associated with V and therefore the swimming
performance.

With respect to the interaction between trial and skill level, as the protocol progressed the sub-
elite swimmers increased more their hip roll angles in relation to the elite ones, especially in
the last 2 trials. A possible explanation could be that the greater decrease in V observed in the
sub-elite group in the last 2 trials resulted in the greater increase of the hip roll in those 2 trials
and vice versa (i.e. increased hip roll led to decreases in V). However, another possible
explanation is the one suggested by Psycharakis and Sanders (2008) that the reduction in
vigour of the kick actions of the swimmers due to fatigue might result in an increase in the hip
roll magnitude. Yanai (2001) speculated that it is paradoxical that swimmers are recommended
to roll more in front crawl in order to increase their V. Increases in roll magnitudes require an
increased demand on arms and legs to generate forces in non-propulsive directions which, in
turn, will reduce the propulsive forces in the swimming direction and will limit V.

To summarise, although the results of the present study evidence that there are differences in
roll magnitudes between swimmers of different calibre, no practical recommendations can be
made due to the complex mechanical association of body roll and propulsion. Thus, the effect
of skill level on roll magnitudes has not been clearly established and further research is
required.
5.5. IVV

5.5.1. Horizontal axis

5.5.1.1. Effect of fatigue

The absolute and relative values of Vmaxx, Vminx and IVVx found in the present study for the elite and sub-elite swimmers are comparable to those reported by other studies (Albery et al., 2005; Figueiredo et al., 2012a; Psycharakis et al., 2010). Vmeanx decreased during the testing protocol. Since it has been found that Vmeanx has a strong linear relationship with both maximum and minimum instantaneous velocities in the swimming direction (Psycharakis et al., 2010), it was anticipated that Vmaxx and Vminx would decrease over the course of the testing protocol. Indeed, Vmaxx and Vminx gradually decreased from 1.99 m·s⁻¹ and 1.50 m·s⁻¹ respectively in trial 1 to 1.85 m·s⁻¹ and 1.40 m·s⁻¹ respectively in trial 11. With respect to IVV in the horizontal direction, IVVx decreased significantly from an average of 0.48 m·s⁻¹ in the first 3 trials to an average of 0.44 min·s⁻¹ in the last 3 trials. No significant changes were observed in Vmaxx%, Vminx% and IVVx% with the exception of a significant difference in Vmaxx% between trial 1 (116.3%) and trial 9 (113.9%). The effect of fatigue in the changes in Vmaxx and Vminx with Vmeanx observed in the present study are in line with the findings of Psycharakis et al. (2010) and Figueiredo et al. (2012a) during a 200-m maximal trial. The findings of the present study also showed that IVVx remained constant during the first 3 trials of interest before it decreased significantly. Psycharakis et al. (2010) and Figueiredo et al. (2012a) reported that IVVx remained unchanged throughout a 200-m trial. The observed reduction in IVVx in the present study may be attributed to the longer testing protocol which probably induced greater levels of fatigue. The resistive forces are proportional to the square of V (Toussaint et al., 2006) and since Vmaxx decreased significantly in the last 3 trials of the testing protocol, the swimmers would have to overcome lower resistive forces which explains the decreases in IVVx. As far as the relative variables are concerned, findings are in
accordance with the results of other studies (Alberty et al., 2005, Figueiredo et al., 2012a; Psycharakis et al. 2010) as no changes in Vmaxx%, Vminx% and IVVx% were reported as an effect of fatigue.

5.5.1.2. Effect of skill level

The elite swimmers were characterised by significantly greater absolute and relative values of Vmaxx, Vminx and IVVx, compared to those of the sub-elite swimmers, with the exception of Vminx% where the sub-elite swimmers had higher values. Psycharakis et al. (2010), found no overall link between IVVx and performance, but noted that in some of the analysed stroke cycles for which significant correlations were observed between IVVx and Vmeanx, the faster swimmers had greater IVVx magnitudes compared to the slower swimmers. According to Barbosa et al. (2006), the greater velocity variations have been linked with increased energy cost, and therefore one would expect the elite swimmers to be characterised by a more constant Vmeanx during the stroke cycle. This notion that lower IVVx values indicate better swimming economy/efficiency has been supported by several authors (Barbosa et al., 2013; de Jesus et al., 2015; Schnitzler et al., 2010; Seifert et al., 2010a; Vilas-Boas et al., 2011). However, according to recent data reported by Figueiredo et al. (2012c), no relationship was found between IVVx and energy cost throughout a 200-m trial, and also the IVVx was inversely correlated with energy cost (r=-0.83) in the first lap, indicating that decreases in IVVx were associated with increases in energy cost. Further, in the aforementioned study of Barbosa et al. (2006), the swimmers were tested in a wide range of velocities (incremental tests) which limits the generalisation of the results with respect to maximal efforts. This limitation combined with the findings of Figueiredo et al. (2012c) suggest that the relationship between IVVx and energy cost should not be used as a performance predictor. In the present study, the elite swimmers displayed higher absolute and relative IVVx magnitudes which can be attributed to the fact that they had to encounter larger resistive forces as they were swimming at higher V. These higher resistive forces probably caused larger magnitudes of acceleration
and deceleration in the stroke cycle and this explains the larger IVVx and IVVx% found in the elite group in relation to the sub-elite group.

Finally, the absolute and relative values of Vmaxx, Vminx and IVVx found in this study for the elite and sub-elite swimmers are comparable to those reported by other studies (Alberty et al., 2005; Figueiredo et al., 2012a; Psycharakis et al., 2010).

5.5.2. Vertical axis

5.5.2.1. Effect of fatigue

The values IVVy and IVVy% of the present study are comparable to those reported by Psycharakis et al. (2010) and Figueiredo et al. (2012a). No changes were observed in the absolute and relative values related to intracycle velocity variations, which indicates that the development of fatigue did not affect those variables. This is also in line with the results of Figueiredo et al. (2012a) and Psycharakis et al. (2010).

5.5.2.2. Effect of skill level

The elite swimmers displayed larger Vmaxy and IVVy, and smaller Vminy% values in relation to the sub-elite ones. The greater Vmaxy and IVVy values observed in the elite group are perhaps associated with the greater Vmaxx and IVVx magnitudes of this group, as it has been suggested that the vertical velocity variations are caused by the vertical components of the forces that a swimmer applies in the water to travel forward (Toussaint et al., 2002). The difference between groups in Vminy% can be simply explained by the differences in Vmeanx (i.e. higher denominator for the elite group with equal numerator for both groups). So far, no scientific evidence exists in the literature supporting the idea that absolute or relative Vmaxy, Vminy or IVVy are linked with swimming performance (Figueiredo et al., 2012a; Psycharakis et al., 2010). The intracycle velocity variations in this axis has been attributed to changes in the magnitude of buoyancy and further research has been suggested with respect to IVV in
this axis especially in breaststroke and butterfly, which are characterised by pronounced vertical movements (Pscharakis et al., 2010).

5.5.3. Lateral axis

5.5.3.1. Effect of fatigue

The magnitudes of the absolute and relative Vmaxz, Vminz and IVVz values in the present study are again comparable with those reported by Pscharakis et al. (2010) and Figueiredo et al. (2012a). No differences were observed in absolute and relative IVVz values and its components throughout the course of the trials. This finding again confirms those of Pscharakis et al. (2010) and Figueiredo et al. (2012a). Although the development of fatigue might cause lateral swaying as a result of an impairment in body alignment (Albery et al., 2005), it seems that this is not the case in the present study.

5.5.3.2. Effect of skill level

In the present study, a significant effect of skill level was found with respect to Vmaxz%, Vminz% and IVVz% with the sub-elite swimmers displaying significantly larger values compared to the elite ones. This data seems to be in accordance with Figueiredo et al. (2012a), who reported a negative correlation between IVVz-Vmeanx and IVVz-SL. Moreover, it has been suggested that sub-elite swimmers are characterised by larger lateral swaying in relation to elite ones (Cappaert et al., 1995) However, Pscharakis et al. (2010) reported no link between IVVz and any performance-related variable. It is evident, that further research needs to be conducted with respect to intracycle velocity variations in the lateral (and vertical) axis in different testing protocols and speeds in order any relationships between velocity variations and performance to be revealed.
6. Conclusion

The purpose of the present study was to investigate the adaptations in the kinematic characteristics of male sprint swimmers during a maximal intermittent training set. Furthermore, the present study sought to examine whether there are kinematic characteristics accountable for the different skill level/performance between elite and sub-elite sprint swimmers and also to explore whether elite and sub-elite swimmers are affected differently by fatigue depending on their skill level. The main findings of the present study are summarised below.

6.1. Summary of the main findings

6.1.1. V, SL, SF and SI
- Swimmers’ V, SL and SI decreased and SF remained constant during the testing protocol.
- Over the course of the trials, elite swimmers achieved higher V, SL and SI than the sub-elite swimmers.
- Elite swimmers managed to maintain their V throughout the maximal intermittent training set by displaying smaller reductions in SL in relation to the sub-elite swimmers.

6.1.2. Relative duration of stroke phases
- During the testing protocol, entry duration remained unchanged, pull and push phase durations increased before they declined, while conversely, release and recovery phase duration decreased before they increased.
- Elite swimmers allocated a longer time in pull and push phases (propulsive phase) in relation to the sub-elite swimmers, whereas the latter swimmers spent more time in the entry, release and recovery phases (non-propulsive phase).

- Elite swimmers adjusted their technique with the development of fatigue in order to spend longer time in propulsive phase compared to sub-elite swimmers.

### 6.1.3. Shoulder and hip roll

- As V decreased during the testing protocol, swimmers rolled their shoulders and hips more.

- Sub-elite swimmers rolled their hips more compared to the elite swimmers, while no differences in the magnitude of shoulder roll were observed between the groups.

- As fatigue developed, the sub-elite swimmers increased their hip roll more compared to the elite swimmers.

### 6.1.4. IVV

- IVVx decreased during the test, while IVVx%, IVVy, IVVy%, IVVz and IVVz% remained unchanged.

- Elite swimmers displayed larger IVVx, IVVx%, IVVy and smaller IVVz%.

### 6.2. Practical implications

The results of the present study highlighted the fatigue-induced changes in kinematic characteristics of elite and sub-elite swimmers. Furthermore, swimmers of different skill level differ in terms of kinematic characteristics related to swim performance. It was also highlighted that, under fatigue conditions, elite swimmers are more capable of maintaining better performance-related kinematic parameters and also adjusting their technique in order to optimise their performance.
The elite swimmers achieved higher V by displaying longer SL and equal SF in relation to the sub-elite swimmers. As it has been widely suggested in the literature, special attention in training should be given in order to encourage swimmers to lengthen their SL. Considering the findings in the literature in conjunction with the results of the present study, longer SL can be achieved through progressive training methods. At the first stage, technical drills should be used focusing on increasing SL. At the second stage, coaches should advise swimmers to adopt the longest SL possible while swimming at imposed low to moderate intensities. At the third stage, at an imposed maximal pace/speed, based on the fact that the energy expenditure is inversely related with SL and positively related with SF, coaches and swimmers should identify the most energetically economical SL-SF relationship. At the last stage, speed and SF are constrained by the coach and the swimmers are exposed to maximal intermittent training sets at race pace trying to maintain their V by minimising the reductions in SL.

In the present study, the sub-elite swimmers, probably due to the less vigorous kicking actions, rolled their hips more in relation to the elite swimmers especially at the last stage of the testing protocol. This highlights the importance of kick training as typically used by the swim coaches.

The findings of the present study challenge the existing literature with respect to IVV in swimming direction. It has been commonly suggested that small horizontal IVV magnitudes are related to high performance, however, in the present study larger IVV magnitudes were achieved by the elite swimmers in comparison to the sub-elite swimmers. At present, no practical implications can be suggested until further research confirms the results of the present study and improves the understanding in the topic. Moreover, further research is needed to clarify the relationship between vertical and lateral IVV with swim performance.

In the present study and particularly for the sub-elite group, the most marked technical changes due to fatigue were observed from trial 7 through the end of the maximal intermittent protocol.
This observation suggests that, in this type of set, coaches should continuously monitor the technical elements of their swimmers (especially beyond 200-m) in order to prevent serious impairments in technique. It is suggested that, for this type of training set, sub-elite swimmers should be exposed to lower training volumes not exceeding the 300-400 m at a time, meaning that swimmers can repeat the set in the same session only after periods of active and/or passive recovery. As the swimmers become more capable of maintaining their technical characteristics, the volume of the training sets can be increased.

Elite swimmers can be exposed to maximal intermittent training sets exceeding 400-m, providing that they satisfactorily maintain their technical elements. As fatigue develops and the swimmers are not able to maintain a constant SL, it is suggested that coaches should ask the swimmers to continue the set by adopting higher SF to counterbalance decreases in SL.
Bibliography


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Appendix

Ethics Application Form

University of Edinburgh

MORAY HOUSE SCHOOL OF EDUCATION ETHICS COMMITTEE

Student Application Form
(This form is for completion electronically)

PROCEDURE FOR ETHICAL APPROVAL

This form should be used for all research carried out by postgraduate students under the auspices of Moray House School of Education. A four-tier system of ethical approval has been developed, as explained in Section 2 on page 2.

This form should be completed by all Postgraduate students (taught or research degree) prior to research commencing. It should be completed in consultation with your main dissertation/thesis supervisor. The final version should be signed by the student and the supervisor and both should retain a copy. A revised form should be submitted if the nature of the research changes significantly during the period of study.

If the research is assessed at Level 0 or Level 1 the form need not be processed by the Moray House Ethics Committee. However a copy of the completed form should be sent to Shona Cunningham, Research Secretary at RKE Office (shona.cunningham@education.ed.ac.uk) for auditing purposes. If the research is considered to be at Level 2 or Level 3 (see Section 2) the application must be sent to Shona Cunningham who will arrange for it to be reviewed by the Moray House Ethics Committee.

(Please note that those students undertaking the Strength & Conditioning MSc and the MSc Performance Psychology should submit applications to the Programme Director of their course rather than the Ethics Committee). Postgraduate research students should also submit a completed application form to their first year board.

Research should not commence until the supervisor(s) and, where necessary, the Ethics Committee have approved the ethics application.

SECTION 1: STUDENT & PROJECT DETAILS

1.1 Student name: Konstantinos Kalitsis
1.2 Programme: PhD
1.3 Supervisor(s): Dr Simon Coleman; Dr Carla McCabe
1.4 Title of Research Project: Effect of performance level on kinematic and metabolic parameters of male sprint swimmers
1.5 Proposed research start date: 12/05/2014
1.6 Project duration: 3 months

SECTION 2: ETHICS CATEGORY & GUIDANCE

2.1 Please tick the box which best describes your proposed research study:

Level 0: your research project is completely desk-based, i.e. does not involve participants. □

Level 1: covers research with participants that is ‘non-problematic’, i.e. the likelihood of physical or emotional risk to the participants is minimal. This may include, for example, analysis of archived data, classroom observation, or questionnaires on topics that are not generally considered ‘sensitive’. This research can involve children or young people, if the likelihood of risk to them is minimal. □

Level 2: covers novel procedures, topics of a more sensitive nature, or the use of atypical participant groups – usually projects in which ethical issues might require more detailed consideration but are unlikely to prove problematic. □

Level 3: applies to research which is potentially problematic in that it may incorporate an inherent physical or emotional risk to participants. √

2.2 Ethical guidelines followed (tick all that apply):

British Educational Research Association (BERA) □
British Sociological Association (BSA) □
British Psychological Society (BPS) □
The British Association of Sport and Exercise Sciences (BASES) √
Other (please write in) □

2.3 Does the project require the approval of any other institution and/or ethics committee?

YES □
NO √

If YES, give details and indicate the status of the application at each other institution or ethics committee (i.e. submitted, approved, deferred, rejected).
SECTION 3: DESCRIPTION OF THE RESEARCH

Please provide a brief description (no more than 500 words) of your research. This should include, as appropriate, the aims and objectives of the study, the research question and/or hypothesis to be investigated, details of the sample, and data collection methods.

Sport performance is the combined result of coordinated exertion and the integration of a variety of factors. These factors can be divided into three categories: the trainable factors (biomechanical, physiological and psychological); the teachable factors (tactics) and others outside the control of the athlete and coach (genetics). Swimming constitutes a demanding sport and all the aforementioned factors determine swimming performance. This study will examine the aforementioned trainable factors, and more specifically the biomechanical and physiological (from a biochemical perspective) ones.

The aim of the present study is to investigate the biomechanical adaptations of elite and sub-elite swimmers during a lactate tolerance set. Another aim of the study is to investigate the acute effect of intensive swimming exercise on the metabolic profile of elite and sub-elite swimmers. Researching the above aims will provide coaches, swimmers and scientists with useful information regarding the differences in adaptations between elite and sub-elite swimmers. In this context, factors that differentiate elite from sub-elite swimmers may be revealed.

Eight elite and eight sub-elite trained adult male swimmers who are specialized in front-crawl sprint events (50-m and 100-m) will participate in this study. To be eligible, the participants are required to be in full training attending at least 6 sessions per week and being familiar with high-intensity interval training sets. Swimmers who smoke or take any type of medication will not be included in the study. Swimmers possessing any kind of injury will be excluded from the study. Before participation in the tests, the participants will be informed of all procedures related to testing followed by signing a medical questionnaire and consent form.

The research testing will be conducted over 3 months and the participants are required to attend one test session which is estimated to last 2 hours. Prior to each testing session, the participants’ anatomic landmarks will be marked with the use of black marker paint and a sponge. Thereafter, each participant is required to follow a specific warm-up in the swimming pool followed by 12 x 50-m swim trials at maximum effort with a work-to-rest ratio to be 1:1. The swimmers will be videoed by 6 digital cameras (4 underwater and 2 above water) during the 12 x 50-m for subsequent kinematic analysis. Finally, the participants are required to give two urine samples, one before the warm-up and one 1 hour after the completion of the testing protocol. All data will be kept confidential and stored safely throughout the study.

If your project is ‘Level 0’ please go now to Section 8.
SECTION 4: PARTICIPANTS

4.1 How many participants do you intend to include in the research? 16

4.2 What criteria will be used in deciding on the inclusion and exclusion of participants in the study?

Inclusion criteria: participants are required to be highly-trained adult male swimmers competing at national or international level and are specialized in front-crawl sprint events (50-100 m).

Exclusion criteria: participants who possess injury, smoke, receive drugs or medication.

4.3 Are any of the participants likely to be:

under 16 years of age? YES ☑
NO ✓

children in the care of a Local Authority? YES ☑
NO ✓

known to have additional support needs? YES ☑
NO ✓

physically or mentally ill? YES ☑
NO ✓

vulnerable in other ways? YES ☑
NO ✓

members of a racial or ethnic minority? YES ☑
NO ✓

unlikely to be proficient in English? YES ☑
NO ✓

in a client or professional relationship with the researchers? YES ☑
NO ✓

in a student-teacher relationship with the researchers? YES ☑
NO ✓

in any other dependent relationship with the researchers? YES ☑
NO ✓

have difficulty in reading and/or comprehending any printed material distributed as part of the study? YES ☑
NO ✓
If YES to any of the above, explain and describe the measures that will be used to protect and/or inform participants (also see section 7 on children & vulnerable adults)

4.4 How will the sample be recruited?
The participants will be volunteers, who meet the selecting criteria, from local swimming clubs and university teams.

4.5 Will participants receive any financial or other material benefits because of participation?

YES □ ☑
NO □

If YES, what benefits will be offered to participants and why?
The participants will be given the videos of the swim trials in order to use it to improve as swimmers.

SECTION 5: POTENTIAL RISKS TO PARTICIPANTS/RESEARCHER

5.1 Could the research induce any psychological stress or discomfort in the participants? YES □ ☑
NO □

If YES, state the nature of the risk and what measures will be taken to deal with such problems.
The participants will perform an intensive training set which will consist of 12 x 50-m trials. This training set will induce fatigue and possibly discomfort. However, all the swimmers will be highly trained and therefore will be familiar with this sort of training sets as part of their training routine. Moreover, throughout the testing sessions, lifeguards will be available at poolside. Finally, the participants will be informed of what is required prior to the experiment protocol and made aware that they can withdraw at any point.

5.2 Does the research require any physically invasive or potentially physically harmful procedures? YES □ ☑
NO □

If YES, give details and outline procedures to be put in place to deal with potential problems.
The participants will give the two urine samples in private cubicles.

5.3 Does the research involve the investigation of any illegal behaviours?

YES ☑
NO □

If YES, give details.

5.4 Is it possible that this research will lead to the disclosure of information about child abuse or neglect?

YES ☑
NO □
If YES, indicate the likelihood of such disclosure and your proposed response to this. If there is a real risk of such disclosure triggering an obligation to make a report to Police, Social Work or other authorities, a warning to this effect must be included in the Information and Consent documents.

5.5 Is there any purpose to which the research findings could be put that could adversely affect participants?

YES ☐ NO ☑

If YES, describe the potential risk for participants of this use of the data. Outline any steps that will be taken to protect participants.

5.6 Could this research adversely affect participants in any other way?

YES ☐ NO ☑

If YES, give details and outline procedures to be put in place to deal with such problems.

5.7 Could this research adversely affect members of particular groups of people?

YES ☐ NO ☑

If YES, describe these possible adverse effects and the protection to be put in place against them.

5.8 Is this research expected to benefit the participants, directly or indirectly?

YES ☑ NO ☐

If YES, give details. The participants will be provided with information on the kinematic and metabolic adaptations when strenuously swimming. This information can be used by swimmers and their coaches in the direction of improving swimmers' weaknesses. This will help the swimmers to reach their maximum potential by improving the training process.

5.9 Will the true purpose of the research be concealed from the participants?

YES ☐ NO ☑

If YES, explain what information will be concealed and why. Will participants be debriefed at the conclusion of the study? If not, why not?
5.10 At any stage in this research could researchers’ safety be compromised or could the research induce emotional distress in the researchers?

YES ☐ NO ✓

If YES, to either or both, give details and outline procedures to be out in place to deal with potential problems.

Before completing Sections 6 - 8 please refer to the University Data Protection Policy to ensure that the relevant requirements relating to the processing and retention of personal data have been met. It is also advised that applicants familiarise themselves with the: “Researcher checklist for compliance with the Data Protection Act” See: http://www.recordsmanagement.ed.ac.uk/InfoStaff/DPstaff/DPResearch/ResearchAndDPA.htm

SECTION 6: PARTICIPANT INFORMATION AND CONSENT

6.1 Will written consent be obtained from all participants? YES ✓ NO ☐

If YES, attach a copy of the information sheet(s) and consent forms (covering project details, confidentiality, freedom to withdraw at any stage of the project).

If NO, please explain why not below:

Please note with regards to consent:
- It would normally be expected that child and parental consent be sought where participants are aged under 18
- If consent cannot or should not be sought for some reason, a clear case and rationale for this must be made below

6.2 Will written consent be obtained from all participants? YES ☐ NO ✓

If YES, attach a copy of the information sheet(s) and consent forms (covering project details, confidentiality, freedom to withdraw at any stage of the project).

If NO, explain why not.
Administrative consent may be deemed sufficient:

a) for studies where the data collection involves aggregated (not individual) statistical information and where the collection of data presents:

(i) no invasion of privacy;
(ii) no potential social or emotional risks:

b) for studies which focus on the development and evaluation of curriculum materials, resources, guidelines, test items, or programme evaluations rather than the study, observation, and evaluation of individuals.

6.3 Will administrative consent (e.g. from a headteacher) be obtained in lieu of participants’ consent? YES ☐ NO ☑

If YES, explain why individual consent is not considered necessary.

6.4 In the case of participants whose first language is not English, will arrangements be made to ensure informed consent? YES ☑ NO ☐

If YES, what arrangements will be made? If translation is required, the inform consent along with the study information will be translated by a professional translator. The translator will be at present to ensure no misunderstanding occur when the participant reads the information.

If NO, give reasons.

SECTION 7: RESEARCH INVOLVING CHILDREN/VULNERABLE ADULTS
Complete this section only if your research involves minors, (i.e. individuals who are less than 18 years) or vulnerable adults.

This section is not applicable to this study.

7.1 All researchers who plan to work directly with children and vulnerable adults should obtain application forms from the Protecting Vulnerable Groups Scheme (PVG Scheme) See http://www.disclosurescotland.co.uk/apply/

Have you obtained the necessary, up to date Disclosure Scotland Clearance?
YES ☐ NO ☐ AWAITING CLEARANCE ☑

7.2 In the case of minors participating in the research on an individual basis, will the consent or assent of parents be obtained? YES ☑ NO ☐
If YES, explain how this consent or assent will be obtained.

If NO, give reasons.

7.3 Will the consent or assent (at least verbal) of minors participating in the research on an individual basis be obtained?

YES ☐ NO ☐

If YES, explain how this consent or assent will be obtained.

If NO, give reasons.

7.4 In the case of participants with additional support needs (special educational needs) will arrangements be made to ensure informed consent?

YES ☐ NO ☐

If YES, what arrangements will be made?

If NO, give reasons.

SECTION 8: CONFIDENTIALITY AND HANDLING OF DATA

8.1 Will the research require the collection of personal information from e.g. universities, schools, employers, or other agencies about individuals without their direct consent?

YES ☐ NO ✓

If YES, state what information will be sought and why written consent for access to this information will not be obtained from the participants themselves.

8.2 Will any part of the research involving participants be audio/film/video taped or recorded using any other electronic medium?

YES ✓ NO ☐

If YES, what medium is to be used and how will the recordings be used?
The participants will be recorded by 6 digital cameras for the subsequent analysis with the use of APAS programme. The video files will be stored on a locked computer.

8.3 Who will have access to the raw data from the research (record forms, documents, electronic media etc.)?
Only the researcher and the supervisors will have access to the raw data. After the completion of the data analysis, the participants will have access to their video files.

8.4 How will the confidentiality of data, including the identity of participants, be ensured?

Only the researcher and the supervisors will have access to the participants’ data. The participants’ identities will be changed to a number format for use during the testing protocol and the analysis. The data will be stored on a computer and a back-up copy will be retained on an external hard drive. Both the computer and the external hard drive will be locked by password. The urine samples, once collected, will be transferred by the researcher into numbered tubes. Each participant will be allocated to a number so that the identity remains confidential. Thereafter, the tubes will be stored in a freezer. Only the researcher will have access to the freezer. Finally, the researcher will analyse the urine samples. After the completion of the study, the urine samples will be destroyed.

8.5 Specify where/by whom the datafiles/audio/video tapes, etc. will be retained after the completion of the period of study, how long they will be retained and how they will eventually be disposed of.

The data will be stored on a computer and an external hard drive. The data will be retained until 2 years after the study. The data will then be deleted and disposed of securely.

8.6 How do you intend for the results of the research to be used?

The results will be used to answer research questions of a PhD project. After this, the results will be published in the form of research articles. Moreover, the results will be given to the participants for improving their performance.

8.7 Will feedback of findings be given to participants? YES □ NO □

If YES, how and when will this feedback be provided?
Swimmers will receive feedback during the testing sessions in the form of performance times. After the data analysis, each swimmer will receive a report of the results from the overall study.

SECTION 9: CONFLICT OF INTEREST

The University has a ‘Policy on the Conflict of Interest’ (see: http://www.docs.csg.ed.ac.uk/HumanResources/Policy/Conflict_of_Interest.pdf

An example of a conflict of interest is given as follows:

“compromising research objectivity or independence in return for financial or non-financial benefit for him/herself or for a relative or friend.” (Policy on Conflict of Interest, University of Edinburgh, p. 3)

The policy also states that the responsibility for avoiding a conflict of interest, in the first instance, lies with the individual, but that potential conflicts of interest should always be disclosed, normally to the student supervisor, line manager or Head of Institute. Failure to disclose a conflict of interest or to cease involvement until the conflict has been resolved may result in disciplinary action.
9.1 Does your research involve a conflict of interest as outlined above

YES ☐ ☑ NO ☐

If YES, give details.

SECTION 10: SIGNATURES

Student signature: [signature] Date: 09/04/2014...

Supervisor signature: [signature] Date: 09/04/2014...

Supervisor signature: [signature] Date: 09/04/2014...

N.B. Have you attached copies of participant information sheet(s) and consent sheet(s) if appropriate? Have you checked through your application to ensure that you have answered all relevant questions?

Please note all completed forms should be sent to Shona Cunningham, Research Secretary, RKE Office, Moray House School of Education (s.cunningham@ed.ac.uk)

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Level 3 Research Testing Statement (NIH-approve 2008)

For the research I propose to obtain additional rough physiological testing. However, the tests will be done under the control of the investigator's ethical principles and will follow the NIH guidelines for such studies. The specific procedures used will be those described in the NIH guidelines, or other ethical guidelines being used in the study. Such tests include intravenous cannulation, direct measurement of blood flow, and measurement of various other parameters (e.g., blood pressure). Special testing (e.g., single or repeated moves, tests of strength and flexibility, and tests of reaction time) will be conducted to assess the following:

1. Cardiovascular and respiratory function.
5. Auditory acuity.

The tests will be conducted with the informed consent of the participants. The tests will be performed in a controlled environment, and the participants will be monitored by trained personnel. The results of the tests will be used to assess the impact of the interventions on the participants' health and well-being. The tests will be conducted in accordance with the NIH guidelines for such studies, and the results will be reported in accordance with the NIH guidelines for such studies.
Swimmers information sheet

Dear swimmer,

Aim of the study
You are invited to participate in a research study which examines the technique and physiological responses of well-trained swimmers at strenuous anaerobic swimming exercise. The aim of the study is to identify the distinct technical and physiological parameters related to swimming performance. The findings of this study are expected to advance the knowledge with respect to technique and physiology in swimming. These findings will therefore aid the coaches to design more effective training programs and help the swimmers to reach their maximum athletic potential.

What is expected of you?
To participate in the study, you will be required to attend a testing session which is estimated to last approximately 2 hours. It should be noted that no changes in your normal training routine are required for your participation in the study. However, intensive training should be avoided during the 2 days preceding the testing session. For this reason, your coach will recommend when you will be tested so that the testing session does not affect your training programme.
During the testing session, your weight and height will be measured. Additionally, three pictures (one from the front and two from either side) will be taken simultaneously. These data will be used for the subsequent calculation of body segment parameters. After that, you will be asked to give a urine sample in a urine collection cup in private surroundings. Once you give the (first) urine sample, you will do a standard warm-up in the pool (around 1000 m) followed by 12 repeats of 50-m on front crawl at race pace corresponding to the second half of the 100-m race. During the set of 12 x 50-m you will be videotaped (under and above water). For the purposes of the technique analysis procedures, prior to the swimming test, your anatomical landmarks and joints will be marked with black wax-based paint applied with a sponge. You will be required to wear fitted trunks as so that each marker can be easily

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identified. After the completion of the swimming test, you will rest for an hour before you give the second urine sample. Note that you will not be allowed to swim-down until after the second urine sample has been given.

**Potential benefits for your participation**

You will be given the video recordings of your swimming test to assist you and your coach in your technique development. On completion of the study, you will have access to the results and findings which will possibly aid your training process.

**Additional Information**

Initially, you will be required to fill in a medical questionnaire and information sheet detailing aspects of your swimming history, injury history and personal details. If you meet the selection criteria, a testing date that suit you will be arranged for you. The testing session will be held at St. Leonard’s Land swimming pool and you will be required to give informed consent. All information obtained, video files and urine samples will remain strictly confidential and anonymous. In any subsequent use of the data, no names will be referenced or any personal information. You should be made aware that you are under no obligation to complete the testing sessions and are at liberty to withdraw at any time. Finally, after the completion of the study all the video files will be removed from any computer and the urine samples will be destroyed.

If you have any questions or concerns at any point throughout the study, please feel free to contact the researcher or the research project supervisors.

Researcher: Konstantinos Kalitsis  
Telephone: 07564216976  
E-mail: kostaskalitsis@gmail.com

Supervisors: Dr. Simon Coleman; Dr. Carla McCabe  
E-mail: simon.coleman@ed.ac.uk; Carla.mccabe@ed.ac.uk
Informed Consent Form

I (print name clearly)................................................................................................................ hereby give my consent to participate in the exercise test(s) explained to me. I fully understand the following aspects of this study:

- The procedures involved and the purpose, details and requirements of the study as well as the possible benefits.
- That I will be required to provide some personal information, swimming history and medical details prior to participation.
- That underwater and above water views of my swimming will be recorded using video cameras.
- That I have been informed of the possible risks or discomfort associated with this study and its design.
- I can withdraw my involvement at any stage of the study without prejudice.
- That the researchers will answer any questions regarding the procedures.
- That I have responsibilities as a participant in informing the researcher of any problems during the investigation and I am aware of these.
- I have been informed that any information or data I provide will be kept strictly confidential and that my identity will be kept anonymous in any presentation of this material.
- My participation in the analysis is not in response to financial or other inducements.

I acknowledge I have received a copy of this form and that I have read and understood the instructions regarding my participation in this study and agree to fulfil these.

I DO/DO NOT grant permission to be recorded by video cameras.

I DO/ DO NOT grant permission for biological samples to be taken, including urine collection.

Date........../........./.........

Signature of the participant........................................................................................................

Print Name................................................................................................................................

Signature of the researcher............................................................................................................

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Swimmers data information

1. Name:
2. D.O.B: 
3. Age:
4. Height (cm):
5. Weight (kg):
6. Number of training sessions per week/ hours training per week:
7. What is your current 100m front-crawl personal best time (short course):
8. What is your current land training
History...........................................................................................................
.........................................................................................................................
.........................................................................................................................
.........................................................................................................................
9. Have you suffered from any previous injuries/pain which affected your swimming
(Please indicate for all injuries/pain)
Where was the injury located/ which side of the body:.................................
Did you have to cease swimming training? For how long:..............................
10. What is your swimming
experience/history:.........................................................................................
.........................................................................................................................
.........................................................................................................................
11. What are your main competitive swimming
events:.............................................................................................................
.........................................................................................................................
.........................................................................................................................
Additional information for day of test Session:

12. What activities/training were you involved in two days prior to this
test?....................
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1.4 Medical Questionnaire

Before participating in the experimental protocol that has been outlined to you we would
like to establish that the exercise is safe for you. Therefore please complete the following
questionnaire. All information given will be treated as strictly confidential.

1. Name:

2. During your swimming career have you participated in a fatiguing ‘anaerobic’ swim
set at maximum effort as part of your swimming training?

Yes/No
3. If yes, did you have any lasting discomfort or unusual after effects or symptoms other than some muscle soreness following that test?
   Yes/No                  If yes, give details:
4. Have you had to consult your doctor in the last six months?
   Yes/No
5. Have you experienced chest pain when performing physical activity?
   Yes/No
6. Have you experienced chest pain when you were not doing physical activity?
   Yes/No
7. Is there a history of early onset heart disease in your family?
   Yes/No
8. Do you lose your balance because of dizziness or do you ever lose consciousness?
   Yes/No
9. Do you have any form of muscular/joint injury that could be made worse by a change in your physical activity?
   Yes/No                  If yes, give details:
10. Do you have or have you suffered from any of the following conditions that could be made worse by a change in your physical activity?
    Diabetes               Heart condition/complaints
    Asthma                 Hepatitis
    Bronchitis             Blood pressure problems
    Viral/bacterial infection
11. Are you presently taking any medication, particularly for blood pressure problems or a heart condition?
    Yes/No                  If yes, give details:
12. Have you had, for any reason, to suspend your normal training for the past two weeks prior to this test?
    Yes/No                  If yes, give details:
13. Is there anything to prevent you from successfully completing the tests that have been outlined to you?
    Yes/No                  If yes, give details:
I ________________________________ declare that the above information is correct at the time of completing this questionnaire.

Date: ......../........./..........  
Signature of Supervisor:

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