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**Comparison of Biomechanical and Physiological
Characteristics between Front Crawl and Back Crawl**

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Abstract

Front crawl (FC) and back crawl (BC) are similar in terms of having alternating contributions of the arms combined with a six beat kick. However, the reason for the faster swimming times of FC than BC has not yet been established. There have been several studies in which the energy expenditure (\dot{E}) of FC and BC were investigated. However, few researchers have compared \dot{E} between the strokes. Also, although there have been some studies for FC using 3D motion analysis, few researchers have applied 3D motion analysis for BC. There have also been some studies in which the relationship between isokinetic torque produced on an isokinetic dynamometer and FC performance has been investigated, however, the relationship between isokinetic torque and BC performance is unclear. Therefore, the aim of this study was to determine why FC is faster than BC by investigating physiological and biomechanical differences between FC and BC.

Ten Portuguese male national level swimmers were recruited for this study. Three studies were conducted to achieve the aim. In the first study, \dot{E} of FC and BC at the same testing speed below the anaerobic threshold were investigated by measuring swimmers' oxygen uptake. Kinematic variables of FC and BC below the anaerobic threshold were also measured by 3D motion analysis in the first study. In the second study, 3D motion kinematics of FC and BC at the same selected speeds were investigated. In the third study, kinematic differences between FC and BC at the same exercise intensities, and correlations between the kinematics and isokinetic muscular torques of the swimmer in FC and BC and their differences were assessed.

Below the anaerobic threshold, \dot{E} of the swimmers in BC was significantly greater than that in FC at the same speed although there were no differences in stroke frequency (SF), stroke length (SL) and stroke index (SI). Swimmers also had significantly higher Froude efficiency (η_F) in FC than in BC. Differences in several kinematic variables (range of motion of the foot, duration of non-propulsive phases, and intra-cycle velocity variation) suggested that swimmers expended greater energy in BC than in FC. Differences in other kinematic variables (body roll angle, hand speed/acceleration, yaw angle fluctuation, centre of mass displacement, and hand/foot displacements) suggested the possibility of resistive impulse being larger in BC than in FC during the stroke cycle. Thus, FC is more economical and efficient than BC because swimmers lose less energy to the water during the non-propulsive phase, and possibly have smaller resistive impulse in FC than in BC at speeds below the anaerobic threshold. At the same selected speeds above the anaerobic threshold, η_F in BC was significantly lower than that in FC, which was due to faster mean 3D hand speed during the stroke cycle in BC than in FC. The faster mean hand speed in BC than in FC was due to the faster 3D hand speed during the pull phase, and longer relative duration of the release and above-water phases in BC than in FC. SI was also larger in FC than in BC, which was due to longer SL in FC than in BC. The longer SL in FC than in BC was due to the longer duration of propulsive phases and probably smaller resistive impulse during the stroke cycle in FC than in BC. At the same selected exercise intensities, FC was faster than BC because of higher SF . The higher SF in FC than in BC was due to the longer duration of the above-water phase in BC than in FC, longer hand path distance during non-propulsive phases in BC than in FC, earlier timing of the hand entry in relation to the underwater phase of the other hand in FC than in BC. SF in both FC and BC was significantly correlated with shoulder adduction isokinetic torque of the swimmers, however, the effect of shoulder isokinetic torque on the difference in swimming performance between FC and BC required further investigation.

In conclusion, FC is faster than BC because swimmers can achieve higher SF in FC than in BC, and FC is more economical and efficient than in BC with indirect evidence that resistive force are greater in BC than in FC.

Lay Summary

Front crawl (FC) and back crawl (BC) are similar in terms of their propulsive mechanism. However, in swimming competitions, swimmers can complete the race in shorter time in FC than in BC in general, and the reason for the faster swimming times of FC than BC has not yet been established. For example, few researchers have investigated which stroke is more economical (which stroke requires less energy in a given time or distance), and there have been no studies in which motion characteristics of FC and BC were compared. There have been some studies in which the relationship between shoulder muscular strength on the land and FC performance has been investigated, however, the relationship between shoulder muscular strength and BC performance is unclear. Therefore, the aim of this study was to determine why FC is faster than BC by investigating differences in energy requirement and motion characteristics between FC and BC.

Ten Portuguese male national level swimmers were recruited for this study. Three studies were conducted to achieve the aim. In the first study, energy requirements of FC and BC at the same swimming speed at an aerobic intensity (which is an exercise intensity where one can keep doing the exercise without exhaustion e.g. walking) were compared. Motion characteristics of FC and BC at this exercise intensity were also compared using a video analysis in the first study. In the second and third studies, motion characteristics of FC and BC at the same swimming speeds and at the same exercise intensities were investigated at anaerobic exercise intensities (at anaerobic exercise intensity, one gets exhausted within a few minutes or within a minute after starting the exercise depending on the intensity level e.g. fast running). The relationships between shoulder muscular strength of the swimmers and motion characteristics in FC and BC were also measured and compared between the strokes in the third study.

At an aerobic intensity, BC required greater energy than FC at the same speed, however, there were no differences in distance per stroke (the distance covered during one cycle of the arm movement) and stroke frequency (the number of complete one arm movement cycle in a given time) between the strokes. Also, results of the first study suggested that swimmers did more work which did not contribute to propulsion in BC than in FC, and there was indirect evidence of larger resistive drag in BC than in FC. Thus, FC is more economical and efficient than BC because swimmers waste less energy and possibly have smaller resistive impulse in FC than in BC at an aerobic exercise intensity.

Similarly, results from the second study suggested that swimmers did greater work which did not contribute to the propulsion in BC than in FC at the same anaerobic swimming speeds. At the same speeds, swimmers also had longer distance per stroke in FC than in BC, which was due to longer time swimmers applied propulsive force to the water, and smaller resistive drag in FC than in BC.

At the same anaerobic exercise intensities, FC was faster than BC because of higher stroke frequency (which means swimmers completed one stroke cycle in shorter time in FC than in BC). The higher stroke frequency in FC than in BC was due to a straight arm motion during the above-water phase in BC (whereas FC had bent arm motion), longer hand path distance in the water in BC than in FC, and earlier hand entry (to the water) timing in FC than in BC.

Stroke frequency of both FC and BC were related to muscular strength swimmers showed during shoulder adduction movement (moving the upper arm down to the side toward the body), however, the effect of shoulder muscular strength on the difference in swimming performance between FC and BC was not found in this study.

In conclusion, FC is faster than BC because swimmers can achieve higher stroke frequency in FC than in BC, and FC is more economical and efficient than in BC with indirect evidence that resistive forces are greater in BC than in FC.

Comparison of Biomechanical and Physiological Characteristics between Front Crawl and Back Crawl



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

I hereby declare that this thesis is entirely my own work. No part of this thesis has been submitted for any other degree or professional qualification.

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List of Symbols and Abbreviations

FC	- Front Crawl
BC	- Back Crawl
FC@BC	- Front Crawl at the speed of back crawl trials
COM	- The centre of mass
SL	- Stroke Length: Distance the swimmer move forward in one stroke cycle
SF	- Stroke Frequency: The number of the stroke cycle the swimmer achieves at a given time
SI	- Stroke Index: The product of stroke length and the mean COM speed during the stroke cycle
IV_{max}	- Intra-cycle maximum velocity: Maximum instant velocity of COM during the stroke cycle
IV_{min}	- Intra-cycle minimum velocity: Minimum instant velocity of COM during the stroke cycle
IVV	- Intra-cycle velocity variation: The difference between the maximum and minimum instant velocity of COM during the stroke cycle.
$3Du$	- Speed of 3D hand motion relative to COM during the stroke cycle
η_F	- Froude efficiency: Ratio of the useful power output to overcome drag to the power required to overcome external forces
\dot{E}	- Energy expenditure: The amount of energy consumed in a given time
AnT	- The anaerobic threshold: The exercise intensity at which the lactic acid begins to increase exponentially
OBLA	- Onset of Blood Lactate Accumulation: The exercise intensity where the blood lactate accumulation reaches 4mmol
v_{AnT}	- The swimming speed at the intensity of AnT
v_{OBLA}	- The swimming speed at the intensity of OBLA
SD	- Standard deviation
CV	- Coefficient of Variation
X-Direction	- The swimming direction
Y-Direction	- The vertical direction
Z-Direction	- The lateral direction (the direction perpendicular to X and Y-Directions)

Chapter One
Introduction

1.1. Background

In competitive swimming, the technique adopted to overcome water resistance and produce propulsion greatly affects performance (E. Maglischo, 2003). To provide useful information for swimmers to improve their technique, it is essential to identify techniques which ensure efficient performance of each competitive stroke. The mechanical efficiency differs among the strokes (Barbosa, Fernandes, Keskinen, & Vilas-Boas, 2008), and therefore coaches must consider the demands of each stroke when setting workloads for swimmers. However, with the possible exception of front crawl, understanding the relationships between swimmers' techniques, swimming efficiency, and swimming economy is limited. In particular, there is a paucity of information in the extant literature regarding mechanisms of motion, economy and efficiency in back crawl.

According to current world records of each stroke (Table 1.1) and 2012 FINA world top 10 ranking (Table 1.2), back crawl is clearly slower than front crawl. However, back crawl resembles front crawl in terms of motion characteristics. Due to the nature of the arm and leg actions, front crawl and back crawl have been often categorised as 'alternating', whereas butterfly and breaststroke have been categorised as 'simultaneous' (Barbosa, Fernandes, et al., 2006; Chollet, Seifert, & Carter, 2008; Morouço, Keskinen, Vilas-Boas, & Fernandes, 2011; Seifert & Chollet, 2009). In both back crawl and front crawl, the majority of swimmers complete six kicks per stroke cycle, and the mechanics of back crawl are very much like those of front crawl (Counsilman, 1968; E. Maglischo, 2003). Also, front crawl and back crawl swimmers roll their bodies around the long axis to facilitate effective use of the upper body lever systems, and to assist the motion of the upper limbs (Psycharakis & Sanders, 2010). In front crawl, rolling the body also enables breathing. In contrast, butterfly and breaststroke swimmers need to raise and lower their bodies to enable breathing, to align the body to position the lever system to generate propulsive force and reduce resistive drag (Costill, Maglischo, & Richardson, 1992), and to generate body wave rhythms that

contribute to propulsive force and reduce resistive force (Sanders, Cappaert, & Devlin, 1995; Sanders, Cappaert, & Pease, 1996).

Table 1. 1: Male world records of front crawl and back crawl in long course events in 2012.

Records (s)	50m	100m	200m
Front Crawl	20.91	46.91	102.00
Back Crawl	24.04	51.94	111.92

Table 1. 2: Top 10 records in 50, 200, and 200m male front crawl and back crawl events in 2012 (Mean \pm SD).

Records (s)	50m	100m	200m
Front Crawl	21.62 \pm 0.15	47.81 \pm 0.31	105.43 \pm 0.99
Back Crawl	24.85 \pm 0.17	52.97 \pm 0.36	115.28 \pm 1.10

However, the factors which contribute to the difference in the swimming records between front crawl and back crawl have not been clarified in the extant literature. To investigate the factors which account for the difference between the strokes, it is useful to refer to a model of variables contributing to swimming efficiency. Figure 1.1 shows the model based on swimming efficiency proposed by Sanders (2011), and the factors in the model can be

divided into several biomechanical/physiological factors (Figure 1.2). These models suggest the importance of assessing these factors in both back crawl and front crawl to explore the differences in performance between the strokes.

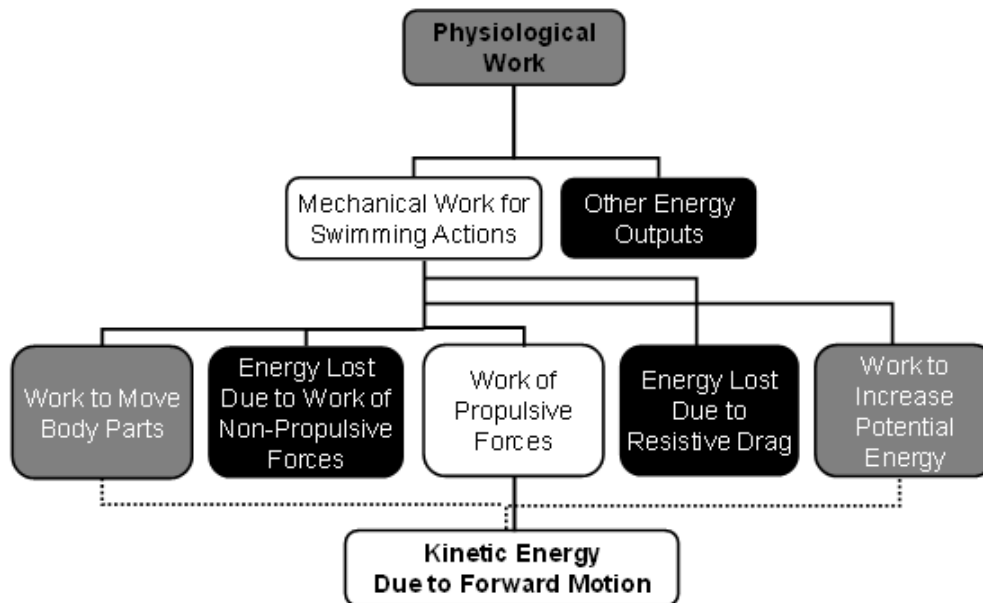


Figure 1. 1: Model of energy and work variables in swimming (Sanders, 2011).

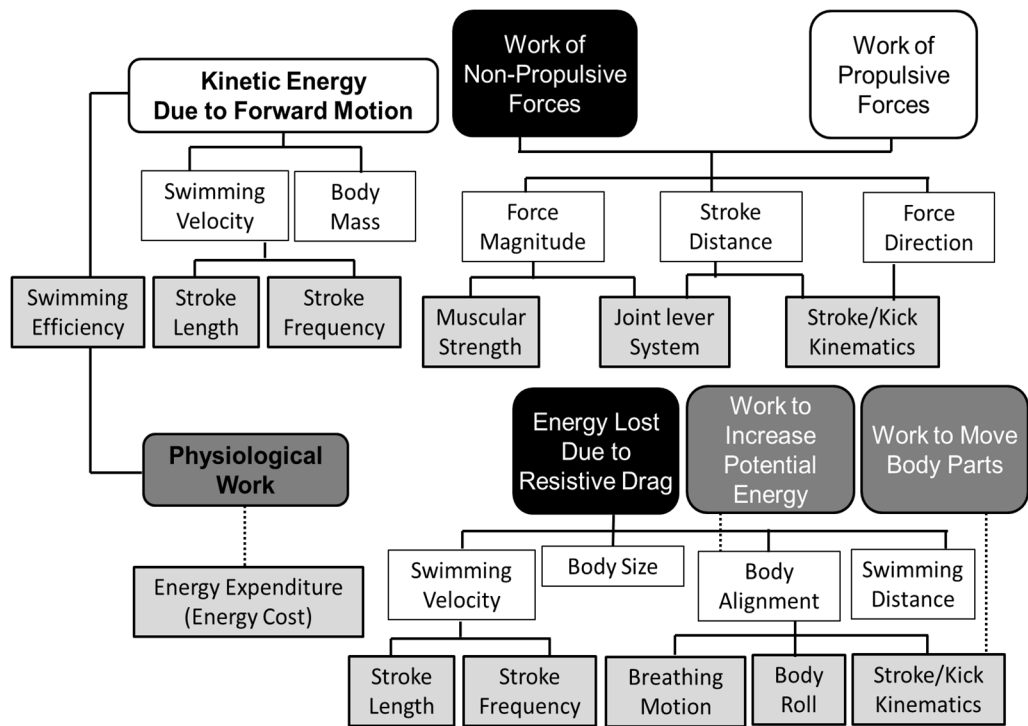


Figure 1. 2: Factors which contribute to swimming performance based on Figure 1.1 (Adapted from Sanders, 2011).

The energy expenditure and energy cost in swimming have been measured to assess the swimming performance from a physiological perspective. In several studies, the energy aspect in several different strokes was measured (Barbosa, Fernandes, et al., 2006; Capelli, Pendergast, & Termin, 1998; Fernandes, Marinho, Barbosa, & Vilas-Boas, 2006; Holmér, 1972; Karpovich & Millman, 1944). Although these studies showed the overall characteristic of energy cost in swimming, the reliability of these datasets is questionable due to a small sample size participating per swimming stroke (ranged from 3 to 8 swimmers for one swimming stroke), because the possibility of producing errors in statistical analysis due to the individual data variability becomes large if the sample size is small. Also, there have been studies in which the energetics of swimmers during front crawl were assessed together

with their kinematic variables (Figueiredo, Barbosa, Vilas-Boas, & Fernandes, 2012; Figueiredo, Pendergast, Vilas-Boas, & Fernandes, 2013; Figueiredo, Zamparo, Sousa, Vilas-Boas, & Fernandes, 2011), yet no such studies are available for back crawl. Furthermore, although several attempts have been made to assess physiological aspects in back crawl (Alves, Gomes-Pereira, & Pereira, 1996; Klentrou & Montpetit, 1992; Smith, Montpetit, & Perrault, 1988), these studies have methodological issues such as inappropriate testing speeds and testing methods which increase the risk of errors. Thus the results of these studies are questionable.

Film-based analysis has been common to assess swimmers' motion characteristics - stroke frequency (SF), stroke length (SL), stroke and kick kinematics, and body roll. There have been three common film-based categories of analysis in swimming, namely race analysis (Arellano, Brown, Cappaert, & Nelson, 1994; Kennedy, Brown, Chengalur, & Nelson, 1990; Mason & Cossor, 2000), two-dimensional (2D) motion analysis (Barbosa, Silva, et al., 2010; Chollet, Chabies, & Chatard, 2000; Osborough, Payton, & Daly, 2010; Seifert, Chollet, & Bardy, 2004; Takeda, Ichikawa, Takagi, & Tsubakimoto, 2009), and three-dimensional (3D) motion analysis (Berger, Hollander, & De Groot, 1999; Cappaert, Pease, & Troup, 1996; McCabe, Psycharakis, & Sanders, 2011; Psycharakis & McCabe, 2011; Psycharakis, Naemi, Connaboy, McCabe, & Sanders, 2010; Sanders & Psycharakis, 2009). Race analysis has an advantage that the researcher can give immediate feedback to the swimmer and the coach in terms of simple race information such as SF and SL , however, the accuracy of the results is questionable since this method cannot reflect any information of the centre of mass (COM). Researchers can obtain more accurate results from 2D motion analysis since this method allows researchers to calculate SF and SL based on COM information if an adequate segmental model is digitised. Also, 2D motion analysis is capable of producing other complex information, such as index of coordination (IdC : Chollet et al., 2000) and intra-cycle velocity variation (IVV : Barbosa, Silva, et al., 2010; Barbosa, Lima, et al., 2006).

Nevertheless, since swimming motion is based on 3D hand and trunk motions, 3D motion analysis is preferable over 2D motion analysis to explore detailed kinematic information in swimming. However, the majority of studies based on 3D motion analysis has been conducted for front crawl analysis, and to date, no 3D analysis has been conducted to quantify back crawl kinematics.

The relationship between muscular strength and swimming performance has been assessed using an isokinetic dynamometer (Li & Sanders, 2007; Miyashita & Kanehisa, 1979; Pichon, Comerri, & Pctiot, 1992) or a biokinetic swim bench (Gehlsen, Grigsby, & Winant, 1984; Neuffer P.D., Costill D.L., Fielding R.A., Flynn M.G., 1987; Potts, Charlton, & Smith, 2010; Tanaka, Costill, Thomas, Fink, & Widrick, 1993). However, almost all of these studies were for front crawl and butterfly, or the basic motion in swimming such as knee flexion/extension. To our knowledge, no studies have been conducted to assess muscular strength and performance in back crawl swimming.

To summarise, many mechanical aspects of back crawl swimming are unknown. In addition, although front crawl and back crawl are mechanically similar, the reason for the superiority of front crawl over back crawl has not been established.

1.2. Aim of the Study

The aim of this study was to determine why front crawl is faster than back crawl, and to investigate if front crawl is more economical and efficient than back crawl.

1.3. Purposes of each Study

To achieve the overall aims, three different studies were conducted.

1. The purpose of the first study was to quantify both physiological and biomechanical differences between front crawl and back crawl at an aerobic exercise intensity to assess whether front crawl is more economical than back crawl at this intensity.
2. The purpose of the second study was to investigate biomechanical differences between front crawl and back crawl at the same anaerobic speeds to assess whether front crawl is more efficient than back crawl at this intensity
3. The purpose of the third study was to explore the differences between front crawl and back crawl at the same anaerobic intensities to assess which kinematic factors make front crawl to be faster than back crawl, and to investigate the relationship between shoulder isokinetic torque and kinematic variables in front crawl and back crawl.

Chapter Two
Literature Review

In order to investigate why front crawl is faster than back crawl, one must have a thorough knowledge and understanding of the biomechanical and physiological aspects in front crawl and back crawl. This is achieved by evaluating and critiquing the literature relevant to front crawl and back crawl. In this section, biomechanical and physiological knowledge related to these strokes were summarised.

2.1. Swimming Performance

To investigate the difference in the performance between front crawl and back crawl, it is necessary to define the swimming performance, and explore the factors which determine the swimming performance.

The prime objective in a swimming race is to complete the race distance in the least time possible (Barbosa, Bragada, et al., 2010; Hay, 1993). To achieve the objective, swimmers need to obtain fast swimming speed and maintain the speed as long as possible. Thus, swimming performance can be defined as the ability of achieving fast swimming speed and maintaining the speed. Swimming race consists of four difference phases – namely the start, stroke, turn, and finish phases and the contribution of the stroke phase on total swimming performance is the greatest among the four (Takeda, Ichikawa, Sugimoto, & Nomura, 2006). Thus, it is important to achieve fast swimming speed and maintain the speed during the stroke phase, and according to Seifert et al. (2004) and Chollet et al. (2008), the swimming speed during the stroke phase of elite swimmers in back crawl was 86.6% of that in front crawl in trials corresponding to their 100m race speed.

Swimming speed (V) during the stroke phase is determined by stroke frequency (SF : cycles·min⁻¹ or cycles·s⁻¹) which is the number of strokes taken in a given time, and stroke

length (SL : $m \cdot cycle^{-1}$) which is the distance covered during each stroke cycle. In other words, from a biomechanical point of view, SF and SL are the primary factors which determine swimming performance (Counsilman, 1968; Hay, 1993; E. Maglischo, 2003). Costill et al. (1985) suggested stroke index (SI) which is the product of V and SL , can be an indirect indicator of efficiency during swimming. This concept is based on the assumption that the longer stroke length equates to a better efficiency, which is the ratio of the useful power/work for thrust to the total power/work, at a given swimming speed (Costill et al., 1985; Longo, Scurati, Michielon, & Invernizzi, 2008; Mason & Cossor, 2000; Sánchez & Arellano, 2002). Although SI is not a variable which reflects the ratio of the useful power production for thrust to the total power production, it has been widely applied in swimming research because it is easy to obtain (Costill et al., 1985; Jürimäe et al., 2007; Sánchez & Arellano, 2002).

From a physiological perspective, maximal swimming performance is determined by the maximal metabolic power of the swimmer and the physiological swimming economy (energy cost: C), which is energy the swimmer expends in a given time or distance (Capelli, 1999; Zamparo, Bonifazi, et al., 2005; Zamparo, Capelli, Cautero, & Di Nino, 2000). The maximal metabolic power and C determine a swimmer's ability to maintain as fast a speed as possible during the race. C is determined by water resistance and the swimming efficiency (η) which is the ratio of useful work (or energy) for thrust to the total work (or energy) the swimmer does (Daniel, 1992; Karpovich & Pestrecov, 1939; Toussaint, Knops, De Groot, & Hollander, 1990; Zamparo, Capelli, & Pendergast, 2011; Zamparo & Swaine, 2012).

These biomechanical and physiological parameters are not completely independent, but have several interrelationships, such as:

- SL and SF have an inverse relationship across all strokes (Counsilman, 1968; Craig & Pendergast, 1979; Hay, 1993; E. Maglischo, 2003).

- SL and \dot{E} are both affected by resistive force (Di Prampero, 1986; Di Prampero, Pendergast, Wilson, & Rennie, 1974; Hay, 1993; Toussaint & Hollander, 1994).
- There is a positive correlation between SF and C (Barbosa et al., 2008; Smith et al., 1988).
- Increasing propulsive force increases the work the swimmer does in a given distance (Toussaint, Janssen, & Kluft, 1991), and thus requires greater \dot{E} .
- There is a positive correlation between η and SI (Longo et al., 2008).

Therefore, to conduct a detailed investigation in relation to the differences in swimming performance between front crawl and back crawl, it is important to consider the differences in all these parameters – V , SF , SL , SI , \dot{E} , η , resistive force, and propulsive force, between the strokes. It is also necessary to investigate the differences in kinematic factors which affect all the above parameters. In the following sections, knowledge related to these parameters is summarised.

2.2. SF , SL , and SI

To consider the differences in SF , SL , and SI between front crawl and back crawl, it is necessary to understand the advantage and the limitations of the use of these parameters. It is also important to know what differences in these parameters between the strokes have been investigated.

2.2.1. Overview of Studies of *SF*, *SL*, and *SI*

SL is one of the most basic factors to assess swimming performance together with *SF*.

Researchers have investigated *SL* and *SF* in swimming and highlighted an inverse relationship between *SL* and *SF* across all strokes (Arellano et al., 1994; Craig & Pendergast, 1979), and linked them with anthropometric characteristics, gender, different strokes, and skill level. Findings include:

- There are negative relationships between *SF* and cross sectional area of axilla and length of arm/leg, and there are positive relationships between *SL* and cross sectional area of axilla/hand/foot and arm length (Grimston & Hay, 1986).
- There is a negative relationships between a swimmer's height and race time in front crawl and back crawl (Kennedy et al., 1990).
- Males achieve longer *SL* than females because of greater height, arm span, foot length, and hand length (Seifert, Chollet, & Chatard, 2007)
- There is no effect of gender in *SF* (Greco, Pelarigo, Figueira, & Denadai, 2007; Seifert, Chollet, & Chatard, 2007).

After the study of Costill et al. (1985) in which the authors suggested the concept of *SI*, *SI* has been accepted as an index of swimming efficiency among researchers. Although it does not reflect the ratio of the useful power production for the thrust to the total power production, Longo et al. (2008) reported a positive correlation between the parameters ($r=0.74$, $p=0.01$) which justified *SI* as an indirect indicator of swimming efficiency. It should be noted, however, that the assumption of longer *SL* represents higher η (when V is the same) means swimmers should be able to achieve the same *SL* and V when they have the same stroke technique and expend the same amount of energy, which is the case only if the swimmers have exactly the same anthropometric and physiological characteristics. Thus, *SI* as an indirect indicator of η can only be established when

compared individuals have the same (or at least very similar) anthropometric and physiological characteristics. For example, it is not appropriate to compare *SI* between male and female swimmers and discuss the difference in η .

Researchers have investigated the relationships between *SI* and gender, skill level, and different strokes and reported:

- *SI* is significantly related to 400-m front crawl time ($r=-0.949$, $p<0.01$, Jürimäe et al., 2007).
- International level swimmers have higher *SI* than national level swimmers (Sánchez & Arellano, 2002).
- Male swimmers have higher *SI* than female swimmers (Sánchez & Arellano, 2002).

There have been few studies in which the differences in *SF*, *SL*, and *SI* between front crawl and back crawl were investigated. However, some researchers investigated the differences in *SF*, *SL*, and *SI* between the four competitive swimming strokes (front crawl, back crawl, butterfly and breaststroke). It was reported that *SF* in back crawl was significantly lower than the other three strokes in 100m events, and *SL* in front crawl and back crawl were significantly longer than those in breaststroke and butterfly (Kennedy et al., 1990). It was also reported that front crawl has the highest *SI* followed by back crawl, butterfly, and breaststroke respectively (Sánchez & Arellano, 2002), and swimmers achieved longer *SL* but lower *SF* in back crawl than in front crawl at maximal speed (Craig & Pendergast, 1979). Craig, Skehan, Pawelczyk, & Boomer (1985) also reported longer *SL* and lower *SF* in back crawl than in front crawl at both 100m and 200m races in the 1976 US Olympic trial (However, the authors also reported similar *SL* between the strokes at both 100m and 200m male races in the 1984 US Olympic trial).

To summarise, studies have reported longer SL in back crawl than that in front crawl, larger SI in front crawl than in back crawl, and higher SF in front crawl than in back crawl. It has to be noted, however, that SF , SL are affected by anthropometric characteristics of the swimmer, and thus, to compare the difference between those strokes with least possible errors, the same group of swimmers should perform the two strokes. However, no attempt has been made to compare SF , SL , and SI between front crawl and back crawl performed by the same swimmers. Also, even though both SF and SL are affected by V (since $V = SF \cdot SL$, no study has been conducted to compare SF , SL , and SI between front crawl and back crawl at the same swimming speed.

2.2.2. Limitations with Studies in SF , SL , and SI

In most of the highlighted studies in previous sections, researchers calculated SL and SI based on total time and/or lap time of the race, which includes the start and turn phases. Swimmers can achieve the fastest speed during the start phase in the race (Takeda et al., 2006), and Blanksby, Gathercole, & Marshall (1996) showed faster 5-m round trip time (total of 10-m) around the turn than mean 10-m time in a 50-m race. Thus, although the calculation based on the race enables coaches and researchers to provide race feedback with quantitative measurements, to include the start and turn phases in the calculation would overestimate SL and SI values. Although similar SL between front crawl and back crawl, and higher SF in front crawl than in back crawl in male swimmers have been reported (Craig et al., 1985; Kennedy et al., 1990), no explanations of the similarity and the difference respectively have been reported.

In recent studies, SF and SL have been assessed based on video analysis. Video analysis would provide more accurate values than the measurement based on race analysis, since the

calculation in video analysis is based on only free-swimming phase whereas other phases (start, and turn phases) are included in race analysis. In several studies in which video analysis was conducted, *SF* and *SL* in front crawl were calculated using the video images of swimmers between 10m and 22.5m points (Chollet et al., 2000; Seifert, Chollet, & Allard, 2005; Seifert et al., 2004). *SF* and *SL* in other swimming strokes were also calculated using this method in several studies (Chollet, Seifert, Boulesteix, & Carter, 2006; Chollet, Seifert, Leblanc, Boulesteix, & Carter, 2004; Chollet et al., 2008; Seifert & Chollet, 2005; Seifert, Delignieres, Boulesteix, & Chollet, 2007). Although this method is supposed to produce more accurate *SF* and *SL* values than race-based calculation, *SF* and *SL* in these studies were all calculated using mean speed of a fixed point (i.e. vertex) during the filmed space in the pool, rather than the centre of mass (COM) of swimmers. It was reported that to use a fixed point as an indicator of a swimmer's speed produced large error in speed profile of the swimmer (Fernandes, Ribeiro, Figueiredo, Seifert, & Vilas-Boas, 2012; Figueiredo, Vilas-Boas, Maia, Gonçalves, & Fernandes, 2009; Psycharakis & Sanders, 2009) and thus, the accuracy of *SL* calculation using a fixed point of the body instead of COM is questionable.

In a small number of studies, *SF* and *SL* have been calculated from COM data obtained using three-dimensional (3D) motion analysis (Figueiredo, Sanders, Gorski, Vilas-Boas, & Fernandes, 2013; McCabe et al., 2011; McCabe & Sanders, 2012). Considering the above-mentioned problems of calculating *SF* and *SL* based on race data and fixed point data, this approach is currently the most accurate method to assess *SF* and *SL*. However, most of the studies using 3D motion analysis have focused on front crawl, and *SF* and *SL* in other strokes have not been considered.

2.2.3. Kinematic and Kinetic Variables which Affect SF , SL , and SI

To date, SF , SL , and SI among different skills/gender/strokes have been investigated in many studies. However, it is also necessary to investigate the factors which determine SF , SL , and SI to give detailed knowledge to swimmers and coaches.

Several authors have suggested the effects of some kinematic and kinetic factors on SF , SL , and SI . Keskinen & Komi (1993) divided a stroke cycle into four phases (catch, pull, push, and recovery phases) and reported that the duration of the catch phase significantly decreased as SF was increased, suggesting the importance of exploring each phase duration together with SF analysis. Also, according to Hay (1993), SF is affected by the moment of inertia of the upper limb about the shoulder, the range of motion through which the arm moves during the stroke cycle, and the torque applied to the upper limbs through the shoulder. Hay (1993) also suggested that SL is determined by the time over which the swimmer applies forces on the water (in other words, duration of the propulsive phase), and the forces exerted on swimmers (propulsive force and resistive force).

The definitions, limitations, and measuring or estimating methods of these kinematic and kinetic factors which affect SF , SL , and SI are summarised in the following sub-sections. For a summary of propulsive and resistive force, see Section 2.5.

2.2.3.1. COM Calculation in Swimming Motion Analysis

To date, several researches have assessed the profile of COM during swimming using different approaches. In the 1980s and 1990s, anthropometric data from Dempster (1955) was widely used to locate swimmer's COM. In the study of Dempster, the anthropometric data were obtained from body segments of cadavers. Each body segment of cadavers were

weighed, then a free swinging pendulum system was used to calculate the moment of inertia of each segment, and immersion methods and a balance plate were used to locate the volume and COM respectively for each segment. C. Maglischo, Maglischo, & Santos (1987) applied Dempster's data for COM calculation in a two-dimensional (2D) motion analysis to assess the difference between hip velocity and COM velocity, and suggested the velocity of the hip does not reflect swimming velocity accurately and it is recommended to assess COM profile in swimming research. Because of the importance of calculating COM profile (displacement, velocity, and acceleration) of the swimmer, Dempster's data has been used by many researchers (E. Maglischo, Maglischo, & Santos, 1989; Sanders et al., 1995; Sanders, Cappaert, Devlin, & Troup, 1992; Sanders et al., 1996).

Another approach for locating COM during swimming is to apply a mathematical model to digitised data. Zatsiorsky & Seluyanov (1983, 1985) quantified the mass, COM and moments of inertia of body segments using a gamma-scanner and derived regression equations for calculating the mass, COM locations and the moments of inertia of the body segments. De Leva (1996) adjusted the equation of Zatsiorsky, since the length of the segments in Zatsiorsky's studies were all calculated based on bony landmarks rather than the centre of joints, which would reduce the accuracy of locating COMs. Using the model of De Leva (1996), which was adjusted from Zatsiorsky's model, for COM calculation, Barbosa, Silva, Sousa, & Vilas-Boas (2003) conducted a 3D motion analysis study to assess the difference in intra-cycle velocity variation (*IVV*) between the hip joint and COM and concluded that the hip does not reflect *IVV* in COM. Other examples of studies in which the equation model by De Leva was used are:

- A 2D motion analysis study in which the effect of a respiratory snorkel on kinematics during swimming was assessed (Barbosa, Silva, et al., 2010).

- 3D motion analysis studies together with \dot{E} or electromyography (EMG) measurement to assess biomechanical/physiological change of swimmers during 200m front crawl (Figueiredo, Barbosa, et al., 2012; Figueiredo, Pendergast, et al., 2013; Figueiredo, Pereira, Gonçalves, Vilas-Boas, & Fernandes, 2011; Figueiredo, Sanders, et al., 2013; Figueiredo, Zamparo, et al., 2011).
- A 2D motion analysis study to investigate the fatigue on kinematic parameters during submaximal and maximal butterfly (De Jesus et al., 2012).
- A 3D motion analysis study of back crawl starts with EMG measurement to identify the effect of the feet position on the wall on muscular activity and start performance (De Jesus, De Jesus, Medeiros, Gonçalves, & Figueiredo, 2015).

Another mathematical model which has been used for swimming research is a BSP (Body Segments Parameters, which are characteristics of each segment, namely segment mass, COM location of segments, and segment moment of inertia) model developed by Ae, Tang, & Yokoi (1992) who applied the elliptical zone method (Jensen, 1978) for developing their model. Takeda et al. (2006) investigated the effect of take-off angle in the start on starting performance (take-off velocity, flight distance and block time) using 2D motion analysis, in which the model proposed in the study of Ae et al. (1992) was applied to calculate BSP data. Takeda, Takagi, & Tsubakimoto (2012) investigated the position and the angle of the back plate on starting blocks on swimming start performance with 2D motion analysis using the Ae et al.'s model. Shimojo, Sengoku, Miyoshi, Tsubakimoto, & Takagi (2014) also applied the Aes' model to assess the effect of the kicking frequency on motion kinematics in maximal undulatory underwater swimming with 2D motion analysis.

The BSP model by Ae et al. (1992) was produced using BSP data of 215 male and 80 female athletes obtained by the elliptical zone method (Jensen, 1978). In the studies of Jensen and Ae, the segments were considered to be composed of 2cm wide elliptical zones to detect

shape fluctuation within the segment. In both studies, the density of each segment was adapted from previous studies (Clauser, McConville, & Young, 1969; Dempster, 1955). Jensen (1978), Yokoi, Shibukawa, & Ae (1986), and Ae et al. (1992) reported small errors between actual body mass and the estimated body mass using the elliptical zone method (1.16-1.82%, 1.65%, and 1.9-2.1% respectively). Wicke & Lopers (2003) investigated the accuracy of the elliptical zone method by comparing segment volumes obtained by the water immersion method with small and large cylinder, and concluded that the elliptical zone method enables researchers to accurately measure limb segment and whole-body volumes. Despite the accuracy of the elliptical zone method, however, the accuracy of Aes' BSP model is still questionable, since individual variation of the segment volume and segments' mass relative to the body mass cannot be reflected.

Also, despite the accuracy of the elliptical zone method, the method has not been in common use because it requires a large digitising table (Deffeyes & Sanders, 2005). To overcome this problem Deffeyes & Sanders (2005) developed a PC based elliptical zone digitising software (eZone). The eZone programme uses the same procedure to obtain BSP data as the Jensen (1978) model, but requires only the investigator a PC, and MATLAB programme. (Deffeyes & Sanders (2005) also reported less than 5% difference between actual body mass and estimated body mass using the programme. (Sanders, Chiu, et al., 2015) assessed the reliability of the eZone programme by measuring within and between assessor variability in obtained BSP data, and reported less than 5% of within-assessor variability and concluded that eZone programme is a reliable tool for BSP calculation. The authors also reported that between assessor variability is slightly larger than within assessors variability, and that to investigate changes of individuals longitudinally, or the effect of bilateral asymmetries, the same assessor should be used to optimise the reliability.

Considering the accuracy of the elliptical zone method and the accuracy and reliability of the programme, eZone improves accuracy of derived kinematics and kinetics of individual

participants. In recent years, the eZone programme has been applied in swimming 3D motion analysis. Psycharakis et al. (2010) and Psycharakis & Sanders (2009) investigated *IVV* in front crawl with 3D motion analysis, in which the eZone programme was used to obtain participants' BSP data. McCabe et al. (2011) and McCabe & Sanders (2012) assessed kinematic differences between sprint swimmers and distance swimmers at sprint and distance paces with COM calculation based on the eZone programme. Oliveira, Chiu, & Sanders (2015) and Oliveira & Sanders (2015) investigated the kinematic patterns associated with force production and the motor lateralization of the dominant and non-dominant lower limbs during the eggbeater kick. The recent use of the elliptical zone method using eZone by many researchers suggests that the eZone programme increased the ease of use and availability of the elliptical zone method for BSP calculation in swimming research.

2.2.3.2. Definitions of Stroke Phases

To investigate differences in the duration of each stroke phase between front crawl and back crawl, it is necessary to consider the phase definition carefully based on the same criteria in both front and back crawl.

A swimming stroke cycle is often divided into several different phases depending on one's purpose. The most simple phase definition is to divide the stroke cycle into two phases – recovery phase (above-water phase) and work phase (underwater phase). Holmér (1974) applied this definition in his study which was to investigate the energy demands for arm-only, leg-only and whole swimming. Richardson, Jobe, & Collins (1979) also used the two-phase definition to investigate the risk factors for shoulder pain during the phases. The use of the two-phase definition has not been common among swimming researchers since it cannot

reflect the complex pull pattern in the water. For this reason, most researchers have divided the underwater phases into several sub-phases.

There are two major ways to divide the underwater phase.

The first way is to divide the underwater phase based on the 3D pull pattern of the swimming strokes. Hay (1993) divided the underwater phase in front crawl, back crawl, and butterfly into three phases (the down-sweep, in-sweep, and up-sweep phases for front crawl and butterfly, and the first down-sweep, up-sweep, and second down-sweep phases in back crawl), and into two phases in breaststroke (the outward-press and inward-scut phases). Costill et al. (1992) and E. Maglischo (2003) used definitions similar to Hay (1993) but with additional phases except breaststroke – five phases in front crawl (entry-stretch phase, down-sweep-catch phase, in-sweep phase, up-sweep phase, and release phase), four phases in butterfly (entry-out-sweep-catch phase, in-sweep phase, up-sweep phase, and release phase), five phases in back crawl (first-down-sweep phase, first-up-sweep phase, second-down-sweep phase, second-up-sweep phase, and release phase). The second up-sweep phase in back crawl was based on the assumption that swimmers can produce slight propulsive force in this phase. However, considering that C. Maglischo et al. (1987) reported that three out of four swimmers had deceleration of the COM after the second down-sweep phase, the assumption is questionable.

The 3D pull pattern definition has been widely applied in swimming research, especially to investigate the upper limbs motion characteristics in front crawl and back crawl using 2D or 3D motion analysis (Alves, 1996; Alves, Costa, & Gomes-Pereira, 1998; Ceccon et al., 2012; Payton, Baltzopoulos, & Bartlett, 2002), sometimes with other analysis such as EMG analysis (Caty et al., 2007; Rouard, Billat, Deschodt, & Clarys, 1997). The phase definitions based on the 3D pull pattern enable researchers to investigate the kinematic and kinetics of swimming in relation to swimmers' actions. However, it is not possible to compare the

characteristics in each phase between different strokes (e.g. front crawl and back crawl) since the phase definition varies between the strokes.

To enable the four strokes to be compared directly, the underwater phase may be divided into the propulsive phase (e.g. pull and push phases) and non-propulsive phase (e.g. entry and release phases). Chollet et al. (2000) divided the arm stroke in front crawl into

- Entry phase: from the time the hand of the swimmer first enters the water to the time at which swimmer's hand starts moving backward.
- Pull phase: from end of the entry phase to the time at which the horizontal displacement of the hand is vertically in line with that of the shoulder (the first propulsive phase).
- Push phase: from the end of the pull phase to the time at which the swimmer's hand exits from the water (the second propulsive phase).
- Recovery phase: from the end of the push phase to the beginning of the next entry phase.

This definition is based on the assumption that propulsive force commences when the swimmer's hand starts moving backward. This definition has been applied for many analyses of coordination (Figueiredo, Morais, Vilas-Boas, & Fernandes, 2013; Komar et al., 2012; Seifert et al., 2005, 2004; Seifert, Chollet, & Rouard, 2007; Seifert, Toussaint, Alberty, Schnitzler, & Chollet, 2010), and kinematic analysis (McCabe et al., 2011; McCabe & Sanders, 2012).

The problem of this phase definition is that the end of the push phase was defined as the time when the hand exits from the water, rather than the last backward movement of the hand – which is more logical since the propulsive phase should end when the hand stops moving backward, as long as the beginning of the propulsive phase is defined as the first backward

movement of the hand. In fact, McCabe et al. (2011) and McCabe & Sanders (2012) redefined the end of the push phase as the last backward movement of the hand. The definition by Chollet et al. (2000) would only be logical if the “backward movement of the hand” was relative to the body (internal reference frame), and not external reference frame. However, almost all researchers who applied the definition did not specify which reference system being used. Nevertheless, considering that Kudo, Sujae, & Jabbar (2012) and Kudo, Vennell, & Wilson (2013) reported that negative hand velocity toward the swimming direction relative to the water generated drag force, and that few evidence on the force generation by the hand backward movement in relation to the body has been reported, it is more logical to define the propulsive phases based on the hand movement relative to the water.

Lerda & Cardelli (2003) and Chollet et al. (2008) divided the stroke cycle of back crawl into six phases – the entry, pull, push, hand lag time, clearing and recovery phases. The definitions of the entry, pull, and recovery phases in back crawl were the same as those in front crawl. The push phase in back crawl was defined as from the end of the pull phase to the last backward movement of the hand. The clearing phase was from the first upward movement of the hand after the push phase, and the hand lag time was defined as the gap time between the push phase and the clearing phase. The author defined the clearing phase (up-sweep phase) as the third propulsive phase, based on the assumption that some swimmers can produce the propulsive force during this phase. However, the assumption that the up-sweep motion of the hand creates propulsive force is questionable (C. Maglischo et al., 1987). Also, it is necessary to apply the same phase definition to front crawl and back crawl to investigate the difference between the two strokes, and thus, it is not appropriate to apply the hand lag-time phase and the clearing phase definitions in this study.

Thus, the most logical way of defining the stroke phase to enable valid comparison of among front crawl and back crawl is to divide the stroke phase into the following five phases

- Entry phase: from the time the hand of the swimmer first enters the water to the time at which swimmer's hand starts moving backward relative to the water.
- Pull phase: from end of the entry phase to the time at which the horizontal displacement of the hand vertically in line with that of the shoulder (the first propulsive phase).
- Push phase: from the end of the pull phase to the time at which swimmer's hand stops moving backward relative to the water (the second propulsive phase).
- Release (clearing) phase: from the end of the push phase until the exit of the hand from the water.
- Above-water phase: from the end of the release phase to the beginning of the next entry phase.

It should be noted that the propulsive phase does not necessarily correspond to the acceleration of COM, since the acceleration of COM depends on net force (sum of propulsive and resistive forces). The propulsive phase is the phase in which the hand is performing propulsive action.

It should also be noted that the sum of propulsive phase durations of right and left hands might not equal to the net propulsive phase duration during the stroke cycle, since it was reported that propulsive phases of the left and right arms were sometimes overlapped in front crawl – this coordination pattern is called ‘superposition’ of the arms (Chollet et al., 2000; Seifert et al., 2004). Yet, there are some doubts on the concept of superposition which is based on the variable called the index of coordination (*IdC*). In the next section, the concept of *IdC* and its limitations are summarised.

2.2.3.3. The Index of Coordination

The index of coordination (*IdC*) is the most widely used variable to quantify the coordination of the arms during front crawl and back crawl (Chollet et al., 2000, 2008; Figueiredo, Morais, et al., 2013; Gourgoulis et al., 2014; Komar et al., 2012; Osborough et al., 2010; Satkunskiene, Schega, Kunze, Birzinyte, & Daly, 2005; Seifert et al., 2005, 2004). This concept was suggested by Chollet et al. (2000), who assessed the arm coordination of French national swimmers in different swimming speeds. *IdC* is calculated using the time lag between the propulsive phase of one arm and the propulsive phase of the other arm. The stroke cycle is divided into four different phases – namely the entry phase (Phase A), pull phase (Phase B), push phase (Phase C) and recovery phase (Phase D) in which Phase B and Phase C are supposed to be the propulsive phase of the arm (for the detailed explanation, see 2.2.3.2). *IdC* is considered as the percentage of the lag time in the stroke cycle. The lag time is calculated for both arms (both from the end of right arm propulsive phase until the beginning of the left arm propulsive phase, and from the end of left arm propulsive phase until the beginning of the right arm propulsive phase), and the mean of the left and right lag times is supposed to be the lag time during the stroke cycle. The arm coordination which has positive time lag (the swimmer has some time lag between the end of the propulsive phase of an arm and the beginning of the propulsive phase of the other arm) is called catch-up, the arm coordination which has negative time lag (the swimmer starts the propulsive phase of an arm before the propulsive phase of the other arm is over) is named superposition, and the arm coordination which does not have any time lag (the swimmer starts the propulsive phase of an arm at the same time of the end of the propulsive phase of the other arm) is opposition (Figure 2.1). In front crawl, it has been observed that

- *IdC* changes from catch-up toward superposition with the increase of the swimming speed (Chollet et al., 2000; Komar et al., 2012; Seifert et al., 2004).

- Swimmers show significantly lower *IdC* in front crawl swimming with leg kick than in front crawl without leg kick swimming (Gourgoulis et al., 2014)
- Elite male swimmers tend to show superposition coordination, but not poor male swimmers or female swimmers (Chollet et al., 2000; Seifert, Chollet, & Chatard, 2007; Seifert, Chollet, & Rouard, 2007).
- Factors which affect *IdC* are *SF*, *SL*, *V*, expertise, and gender. Height and arm span are not correlated to *IdC* (Seifert, Chollet, & Rouard, 2007)

IdC has also been calculated in back crawl. Lerda & Cardelli (2003) and Chollet et al. (2008) applied *IdC* concept to back crawl analysis. Since back crawl contains different stroke movements from front crawl, additional phase (clearing phase) was added in the definition of stroke phases (see 2.2.3.2). In their study, it was reported that contrary to the above-mentioned results in front crawl studies, swimmers used only catch-up coordination regardless the swimming speed. However, to compare *IdC* between front crawl and back crawl is not appropriate since *IdC* in front crawl and *IdC* in back crawl are based on different phase definitions. Indeed, Lerda & Cardelli (2003) calculated *IdC* in back crawl based on not only back crawl phase definition, but also the same phase definition of that in front crawl and showed ‘superposition’ pattern in back crawl. Nevertheless, it has not been discussed which *IdC* calculation should be applied for back crawl *IdC* analysis.

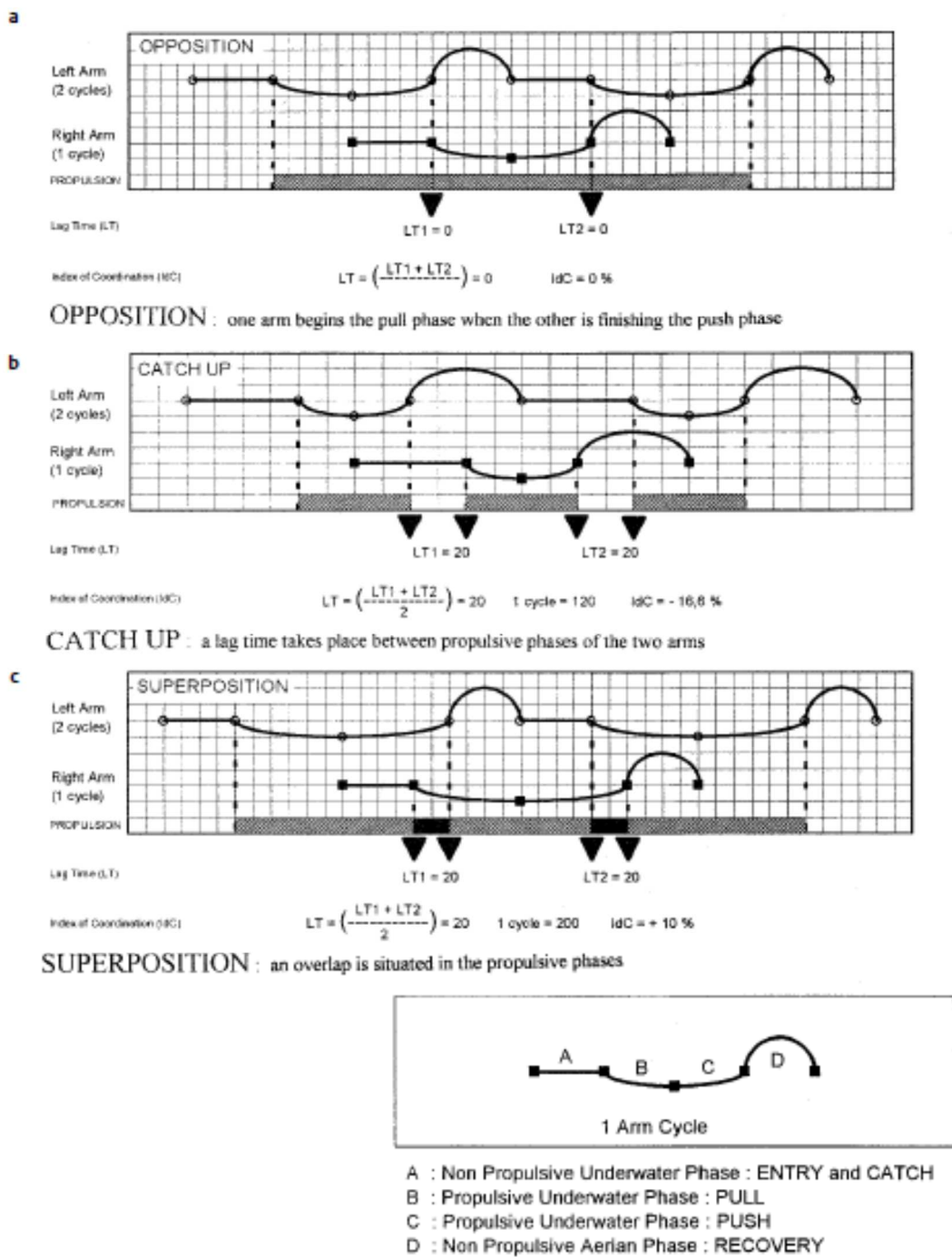


Figure 2. 1: Calculation of IdC, from Chollet et al. (2000).

There are also an issue and limitations in the studies in which *IdC* analysis was applied. The issue is that it is unclear whether the start of the hand backward motion (which is supposed to be the beginning of the propulsive phase in both front crawl and back crawl) and the end of the hand backward motion (which is supposed to be the end of propulsive phase in back crawl) are based on the motion relative to the water (external reference) or the body of the swimmer (internal reference). Thus, it might be possible that the *IdC* based on different reference systems have been discussed as the same concept. The only study which has the clear statement regarding the reference system is the study by Gourgoulis et al. (2014) in which kinematic variables during maximum front crawl swimming of female swimmers were measured. In the study of Gourgoulis et al. (2014), the external reference system was applied to calculate *IdC* of the arms, and the authors showed more than 10 % lower *IdC* than another study which calculated *IdC* of female swimmers during 100m front crawl trials. Considering that swimmers should show higher *IdC* in maximum speed front crawl than 100m speed front crawl (Chollet et al., 2000; Seifert et al., 2004), and *IdC* during maximum speed front crawl trials in the study of Gourgoulis et al. (2014) were much lower than that in 800m speed front crawl or even 3000m speed front crawl in other studies (Chollet et al., 2000; Seifert et al., 2004), there is a doubt that these *IdC* values might have been based on different methodology (i.e. different reference systems). A limitation of most of *IdC* studies is that the analysis is based on observing video image without any calibration (Chollet et al., 2000, 2008; Lerda & Cardelli, 2003; Satkunskiene et al., 2005; Seifert et al., 2004; Seifert, Chollet, & Chatard, 2007; Seifert, Chollet, & Rouard, 2007; Seifert, Toussaint, et al., 2010) which increase the chance of producing errors in distinguishing each stroke phase. Another limitation is that *IdC* does not necessarily reflect the timing of the rotation of left and right arms, because it is also affected by the relative duration of each phase (Chollet et al., 2000, 2008; Osborough et al., 2010). Theoretically, swimmers can change *IdC* without changing the timing of the rotation of left and right arms (Figure 2.2), and thus, it cannot be explained if the change is caused by the timing of arm rotation or the change of relative duration of the

arm propulsive phase or both. To assess if the relative duration of each phase or the timing of the arm rotation are changed, these parameters should be assessed respectively. Although there have been no studies which quantified the timing of the rotation of the arms, it can be assessed by determining the timing of an event of one arm movement relative to the other arm stroke cycle (e.g. to determine the timing of the hand entry of an arm relative to the stroke cycle of the other arm).

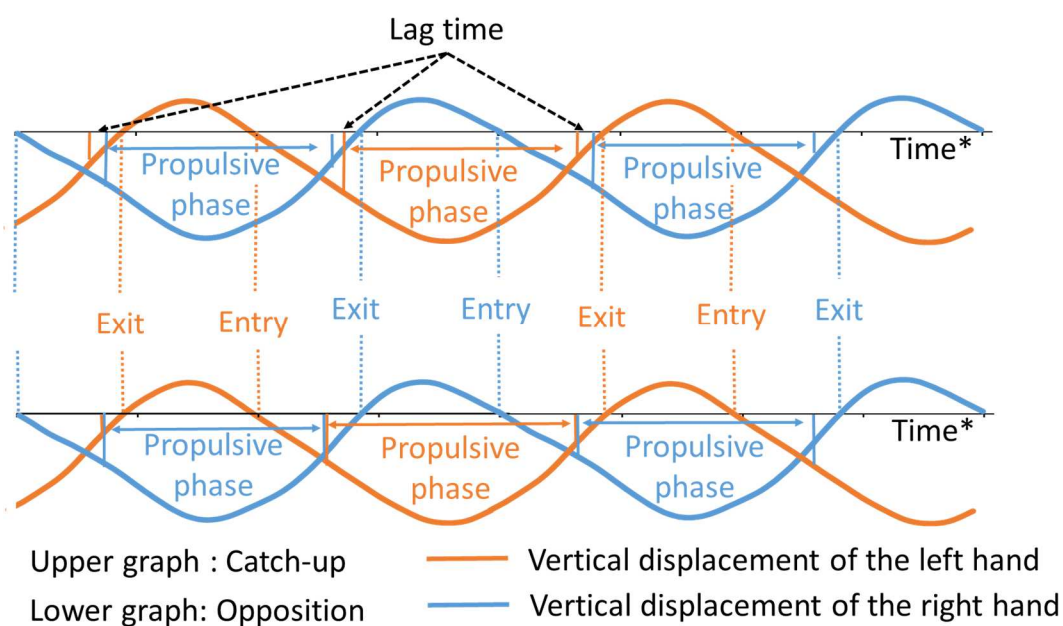


Figure 2. 2: Theoretical example of changing *IdC* without changing the timing of the rotation of left and right arms.

2.2.3.4. The Range of Motion of the Upper Limb, Hand Path, and Elbow Angle during Swimming

There have been few studies which investigated the direct effect of ROM of the arm on SF or swimming performance, however, it is logical that ROM of the upper limbs affects SF since the longer the hand path distance in the stroke cycle, the longer the duration of the stroke cycle if everything else is the same (Hay, 1993). Considering that back crawl has lower SF (see Section 2.2) and swimmers have more complex underwater stroke (i.e. two-peak pattern pull, or three peak pattern pull: E. Maglischo, 2003) and thus perhaps larger ROM of the arm during the underwater phase, ROM might be responsible for the difference in SF between the two strokes.

A useful way of investigating ROM of the upper limbs during a stroke cycle is to assess hand path during the stroke cycle. Using a computer simulation study, Nakashima, Maeda, Miwa, & Ichikawa (2012) reported that the swimmer changes the hand path pattern and has a larger ROM to increase the stroke cycle time (thus, decreases SF). Swimmers move their hands not only in a backward direction, but also in lateral and vertical directions, and thus, swimmer's hand path in lateral and vertical directions has been investigated by many other researchers using computer simulation and experimental methods (Hay, Liu, & Andrews, 1993; Liu, Hay, & Andrews, 1993; Payton et al., 2002; Payton, Bartlett, Baltzopoulos, & Coombs, 1999; Payton, Hay, & Mullineaux, 1997). However, few researchers have focused on the relationships between lateral/vertical hand displacements and SF except the aforementioned study by Nakashima et al. (2012). Another way of assessing ROM of the hand is to investigate the distance of the hand traveling trajectory throughout the underwater stroke phase relative to the COM, because SF is determined by the stroke cycle time which is determined by the distance of the hand trajectory during the stroke cycle and the hand speed. Although there have been no studies in which the distance of the hand trajectory was

investigated, it is necessary to assess the variable in front crawl and back crawl considering its possible effect on the difference between front crawl and back crawl.

2.2.3.5. Torque Measurement in Swimming

As mentioned above, SF is affected by the torque applied on the upper limbs in swimming. Considering that SF in back crawl is lower than that in front crawl (Kennedy et al., 1990), the muscular torque the swimmer produces in the water might be different between front crawl and during back crawl.

It is difficult to measure the torque during swimming since the force the swimmer applies on the water through his/her upper limbs cannot be measured. However, the relationship between swimming performance and shoulder torque have been investigated using shoulder isokinetic torque measured on the land. Miyashita & Kanehisa (1979) reported a significant negative correlation ($r=-0.73$) between 100m front crawl personal best records of 35 swimmers and their isokinetic shoulder extension torque measured at the angular speed of 210 degrees·s⁻¹ using a dynamometer. Batalha, Raimundo, Carus, Barbosa, & Silva (2013) reported a significant increase of shoulder internal rotation torque of swimmers throughout 32 weeks of competitive swimming season without any dry-land training, but not shoulder external torque. The result of Batalhas' study suggested the importance of shoulder internal rotation in swimming. Although the authors did not conduct any motion analysis to assess internal rotation movement during swimming, it has been reported that swimmers use shoulder internal rotation during the swimming strokes (especially during front crawl) in other studies (Ceccon et al., 2012; Olivier, Quintin, & Rogez, 2008).

These previous studies suggested the importance of shoulder extension and shoulder internal rotation torque in front crawl. Although there has been no study in which the correlation between back crawl performance and shoulder isokinetic torques was investigated, there have been studies which suggested the possible difference between front crawl and back crawl in terms of the torque-performance relationship. Perry et al. (1992) and Pink et al. (1992) reported that the primary shoulder movement during back crawl is shoulder adduction, rather than shoulder extension. Thus, it is possible that swimmers applied propulsive forces to the water via shoulder adduction torque, which might affect the difference of swimming performance between front crawl and back crawl since shoulder extension can produce larger isokinetic torque than shoulder adduction, and therefore, allow faster movement of the hands through the water, than shoulder adduction (Cahalan, Johnson, & Chao, 1991).

2.2.3.6. Elbow Joint Angle in Swimming

A kinematic factor which affects the hand path (see 2.2.3.5) of the swimmer is elbow joint angle. There have been studies in which relationships between elbow joint angle and the hand path were discussed. Payton et al. (1997) conducted a simulation study to investigate the effects of body roll and elbow flexion on the hand path, and reported that maximum elbow flexion from 60 to 90 degrees increases medial hand motion. Although it was speculated in later studies that the model used by Payton et al. (1997) did not reflect actual swimmer's motion (Payton et al., 2002, 1999), it is logical that elbow joint angle affects the lateral hand displacement considering that smaller elbow angle causes the hand to cross, or be close to, the medial line of the body at a given elbow displacement (Figueiredo, Kjendlie, Vilas-Boas, & Fernandes, 2012). In fact, Payton et al. (1999) reported that swimmers

achieve their insweep motion using elbow flexion. In front crawl, elbow joint angle of swimmers has been investigated throughout the stroke cycle and it has been generally suggested that swimmers have the smallest elbow angle during the middle of the stroke (Figueiredo, Sanders, et al., 2013; McCabe et al., 2011; McCabe, Sanders, & Psycharakis, 2015; McCabe & Sanders, 2012). The data supports the argument that elbow flexion contributes to the insweep motion of the swimmer, in other words, the lateral movement of the swimmer. In back crawl, however, there have been few studies in which elbow joint angle during back crawl was investigated. Elbow joint angle during back crawl was described by Cappaert (1999) in which the mean elbow angles during the downsweep and upsweep phase in back crawl were investigated. However, the author did not report the pattern of elbow angle throughout the stroke cycle, and thus, it was unclear how swimmers changed their elbow angle (as well as the hand path). Pink et al. (1992) reported that swimmers kept flexing their elbow as the hand approached their thorax and the elbow started extending as it travelled away from the thorax. However, the study by Pink et al. (1992) was based on electromyography analysis and elbow angle change of the swimmers during the stroke was unclear. Considering that elbow angle affects the hand path of the swimmer during the stroke cycle, which are responsible for SF of the swimmer, it is important to assess the difference in elbow joint angle between front crawl and back crawl for the detailed investigation of the difference in SF between the strokes.

2.3. Measurement of the Energy Expenditure in Swimming

To investigate the difference in the energy expenditure and the energy cost between front crawl and back crawl, it is necessary to understand the definitions of the energy expenditure and the energy cost, how the physiological energy is supplied in the body, and which

physiological factors should be investigated to measure the energy expenditure during the strokes. It is also important to understand the accuracy of the energy measurement in swimming.

2.3.1. Energy Expenditure and Energy Cost in Swimming

In general, the energy expenditure is considered as the energy expended during the day, or during the exercise tested, whereas the energy cost is supposed to be the rate of the energy expenditure (Katch, McArdle, & Katch, 2011; McArdle, Katch, & Katch, 2014; Schmidt-Nielsen, 1971; Waters, Perry, Antonelli, & Hislop, 1976). However, there have been no obvious definitions regarding the unit of the energy expenditure and the energy cost. For example, McArdle et al. (2014) and McArdle, Katch, & Katch (2010) referred units of kCal and $\text{kCal}\cdot\text{min}^{-1}$ as the energy expenditure, however, $\text{kCal}\cdot\text{min}^{-1}$ can also be considered as the energy cost since it is the rate of the total energy expenditure normalised by the time. In fact, Waters et al. (1976) defined the energy cost as the amount of energy consumed per minute or meter, or rate of the energy divided by maximum aerobic capacity. On the other hand, Zamparo, Bonifazi, et al. (2005) defined the energy cost as the amount of metabolic energy spent in transporting the body mass of the subject per unit of distance ($\text{kJ}\cdot\text{km}^{-1}$ or $\text{J}\cdot\text{m}^{-1}\cdot\text{kg}^{-1}$). These different definitions indicate that the definitions of the energy expenditure and the energy cost vary among researchers and studies.

Nevertheless, in swimming research, the energy expenditure is often considered as the amount of energy consumed per minute (\dot{E}), such as $\text{Cal}\cdot\text{min}^{-1}$ (Karpovich & Millman, 1944), or $\text{mlO}_2\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (Barbosa et al., 2005; Barbosa, Bragada, et al., 2010; Barbosa, Fernandes, et al., 2006; Fernandes, Billat, et al., 2006). On the other hand,

the energy cost is often considered as the energy expended in a given distance (C) in swimming research, such as $\text{mlO}_2 \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$ (Barbosa et al., 2005), $\text{kJ} \cdot \text{m}^{-1}$ (Figueiredo, Barbosa, et al., 2012), $\text{mlO}_2 \cdot \text{m}^{-1}$ (Costill et al., 1985), $\text{J} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}$ (Barbosa, Bragada, et al., 2010; Komar et al., 2012; Zamparo, Pendergast, Termin, & Minetti, 2002). In accordance with the previous swimming researches, in this study, \dot{E} indicates the energy expended in a given time, and C signifies the energy consumed in a given distance, whether these units are normalised by other variables (such as body weight) or not.

2.3.2. Overview of the Energy Metabolism during Physical Exercise

According to McArdle et al. (2014), the primary energy source for contraction of muscle is adenosine triphosphate (ATP) which releases energy when it is broken down to adenosine diphosphate (ADP) and a phosphate ion (Pi). The amount of ATP stored in the body is limited (80 to 100 g) which is only enough for several seconds all-out exercise (McArdle et al., 2010). Thus, ATP needs to be supplied constantly via metabolism of phosphocreatine (PCr, which consists of phosphate and creatine) and ingested food in the form of carbohydrates, lipids, and proteins (McArdle et al., 2010). There are three stages to recycle ATP, namely the ATP-CP system, actacid system, and aerobic system. In the ATP-CP system, ATP is resynthesised using PCr and ADP and in the actacid system, ATP is produced using the blood glucose and muscle and liver glycogen (E. Maglischo, 2003). Those two systems are categorised as the anaerobic resynthesis since they do not require oxygen during the resynthesis process. In the aerobic system, ATP is resynthesised using the

oxygen, blood glucose, muscle and liver glycogen, and adipose and intramuscular fat (E. Maglischo, 2003).

In terms of the speed of recycling ATP, the ATP-CP system is the fastest, actacid system is the second fastest, and aerobic system is the slowest method to start recycling ATP. On the other hand, the method that can recycle ATP for the longest duration is the aerobic system followed by actacid system and the ATP-CP system (E. Maglischo, 2003; McArdle et al., 2014). Because of these characteristics of each metabolic system, the ATP-CP system is used at the first few second of the exercise, then actacid system and aerobic system follow. The ATP-CP system and actacid system do not require oxygen during its procedure to produce energy, whereas oxygen is essential during aerobic system. Since it is possible to know the amount of the oxygen that is used for aerobic metabolism from the ratio of the oxygen and the carbon dioxide in the inspired and the expired gas, aerobic \dot{E} is often estimated using the oxygen uptake value - $\dot{V}O_2$ (McArdle et al., 2014, 2010). On the other hand, it is difficult to estimate the energy based on the ATP-CP system and actacid system because of technical limitations (Bangsbo et al., 1990; Wertheim, Kemper, & Heus, 2002). In the next section, studies of \dot{E} measurement in swimming using $\dot{V}O_2$ and some attempts to assess swimmer's anaerobic energy are summarised. The benefits and limitations of each method are also considered.

2.3.3. Methods of Energy Expenditure Measurement in Swimming Research

In this section, aerobic \dot{E} measurement in swimming using swimmer's $\dot{V}O_2$ and anaerobic \dot{E} measurement in swimming (outcomes, benefits and limitations) are summarised in different sub-sections.

2.3.3.1. Aerobic Energy Expenditure Measurement in Swimming and Accuracy and Reliability of Oxygen Uptake Measurement Apparatus Used in Swimming Research

There are two common methods of measuring aerobic \dot{E} in swimming research using swimmer's $\dot{V}O_2$.

The first method is to measure $\dot{V}O_2$ during swimming directly using respiratory valve, hose, and the Douglas bag during swimming. Using this method, Holmér (1972) compared oxygen uptake and heart rate of 12 swimmers (6 swimmers swam breaststroke, 5 swimmers swam front crawl, and 1 swimmer swam back crawl) and concluded front crawl was the most economical stroke followed by back crawl and breaststroke, although the author reported similar \dot{E} values between front crawl and back crawl at low speed in another study (Holmér, 1974). Di Prampero et al. (1974) examined energetics of swimming by calculating mechanical efficiency and oxygen uptake, and observed that \dot{E} during swimming at a given speed is a linear function of the total drag the swimmer has to overcome. Although the direct $\dot{V}O_2$ measurement enabled researches to investigate physiological aspects of swimming, the apparatus (the Douglas bag, huge valves and hoses) often limited swimmer's movement which was considered to be a large limitation of this method (Sousa et al., 2014).

The second method which has often been used to measure $\dot{V}O_2$ during swimming is the backward extrapolation method, which is an indirect measurement of the swimmer's $\dot{V}O_2$ during swimming. Montpetit, Léger, Lavoie, & Cazorla (1981) introduced a method for measuring $\dot{V}O_2$ during swimming, using the backward extrapolation of the $\dot{V}O_2$ recovery curve to time of zero. This method has been preferred over the above mentioned direct measurement of $\dot{V}O_2$ during swimming since the backward extrapolation method allows swimmers to swim freely without any restriction of apparatuses. Costill et al. (1985) compared $\dot{V}O_2$ during a tethered swimming and $\dot{V}O_2$ after the tethered swimming, and

reported that $\dot{V}O_2$ immediately after the swimming ($\dot{V}O_2$ from 0s to 20s after the swimming) was highly correlated with $\dot{V}O_2$ during a tethered swimming ($r=0.98$).

Using this method, Smith et al. (1988) examined the characteristic of the aerobic demand of backstroke and suggested that - 1) the \dot{E} of backstroke may be a linear function of velocity, 2) oxygen uptake during backstroke is affected by body size and swimming technique, 3) even among elite swimmers, there is huge inter-individual variation in the C (up to 15%), 4) the \dot{E} of backstroke is in order of 11-13% greater than front crawl, and 5) submaximal C are highly related to maximal swimming performance. These physiological characteristics of back crawl are similar to those of front crawl which were reported in different studies (Costill et al., 1985; Holmér, 1974; Pendergast, Di Prampero, Craig, Wilson, & Rennie, 1977). Klentrou & Montpetit (1992) compared C of back crawl between male and female swimmers and concluded female backstroke was more economical than male due to the smaller drag of females. They also compared the C of the backstroke with front crawl which had been obtained in another study and reported backstroke is slightly costlier than front crawl at similar speed. The difference of C between front crawl and backstroke were examined by Alves et al. (1996). In the study of Alves et al, it was concluded that the difference of C between front crawl and backstroke ranged from 16% for a swimming velocity of $1.1 \text{ m}\cdot\text{s}^{-1}$ to 32% for the velocity of $1.3 \text{ m}\cdot\text{s}^{-1}$. However, in the study of Alves et al. (1996), the swimming speeds were so high that there was possibility that the results contained errors due to the use of anaerobic energy which could not be estimated from oxygen uptake value.

The backward extrapolation method has an advantage that swimmers can swim without any hindrance to the movement. On the other hand, it was suggested that this method had to fulfil many conditions, namely - 1) the exercise has to be progressive and continuous and leads to exhaustion in more than 4-5 minutes, 2) there should not be a gap between the end of the exercise and the beginning of the gas collection, 3) the gas collection has to be started at the

beginning of expiration and be stopped at the end of expiration approximately 20 seconds later from the first expiration, 4) the exercise should not be supra-maximal and not less than 5 minutes. Although the accuracy and reliability of the backward extrapolation method in swimming research has been established (Costill et al., 1985; Montpetit et al., 1981), other researchers have reported that the method contains risks of possible errors and not reliable (Lavoie, Léger, Montpetit, & Chabot, 1983; Pinna et al., 2013; Sousa et al., 2014), because this method requires swimmers to hold their breath completely from the end of the testing stage until putting the mouth piece on their face, but there is great possibility of leak of the expired gas during this process (Sousa et al., 2014).

To overcome the above mentioned problems of the two methods, swimming researchers have often used portable gas analysers and respiratory snorkel, which have been developed since the 1990s (Gayda et al., 2010). While the use of the Douglas bag did not allow researchers to collect the expired gas in the middle of the pool because of its size, the small size and light weight of portable analysers made it possible to conduct the measurement in the middle of the swimming pool. Also, while huge valves and hoses have been often supposed to restrict swimmer's movement, the effect of respiratory snorkels on the swimmer's movement is rather small. In fact, Barbosa, Silva, et al. (2010) compared kinematic differences in front crawl with and without a respiratory snorkel, and concluded that the snorkel did not change swimmers' *SF*, *SL*, and *SI* in the middle of the pool. The accurate measure of $\dot{V}O_2$ during swimming in the middle of the pool enabled researches combining $\dot{V}O_2$ measurement and other measurements, such as electromyography or 3D motion analysis (Figueiredo, Barbosa, et al., 2012; Figueiredo, Zamparo, et al., 2011; Zamparo, Pendergast, Mollendorf, Termin, & Minetti, 2005).

In recent swimming research, the combination of K4b² portable gas analyser and a respiratory snorkel has often been used for the energy expenditure measurement. Reliability of the portable gas analyser has been investigated by Duffield, Dawson, Pinnington, & Wong

(2004) who reported that the difference of test-retest \dot{V}_{O_2} variables fell within the 95% confidence levels. Accuracy of both the snorkel and the gas exchange system have been investigated by comparing \dot{V}_{O_2} with portable gas exchange system and the snorkel with \dot{V}_{O_2} with other gas collecting methods and devices such as the Douglas bag method, respiratory valves and hoses. Doyon, Perrey, Abe, & Hughson (2001) compared \dot{V}_{O_2} of athletes during cycle ergometer exercise at various exercise intensities measured using the K4b² system and a mixing chamber method (which is the measurement of the amount of heat produced by a participant enclosed within a small chamber, and thus, supposed to be an accurate method to measure the energy expenditure). In the study of Doyon et al. (2001) it was reported that there were no differences between the \dot{V}_{O_2} measured by the two methods at any exercise intensities, and thus, the K4b² system produced accurate results. Parr, Strath, Bassett, & Howley (2001) investigated the accuracy of the K4b² system by comparing \dot{V}_{O_2} measured using the K4b² system with \dot{V}_{O_2} measured by Douglas bag method during cycle ergometer exercise, and reported no significant difference in \dot{V}_{O_2} measured by the two method. On the other hand, McLaughlin, King, Howley, Bassett, & Ainsworth (2001) reported significantly lower \dot{V}_{O_2} in the K4b² method than that in the Douglas bag method, which was conducted using a similar method as Parr et al. (2001). Nevertheless, McLaughlin et al. (2001) suggested that the difference was due to extremely small standard deviation, and \dot{V}_{O_2} measured using K4b² method was still acceptable since the difference was very small at any exercise intensities (between 0.88 and 0.92 ml O_2 ·mM⁻¹·kg⁻¹, regardless the exercise intensities). Cosmed Ltd. has produced respiratory snorkels for the use of K4b² during swimming, which have been used in swimming research. Baldari, Fernandes, Meucci, Ribeiro, & Guidetti (2013) investigated the accuracy of the newest snorkel produced by Cosmed Ltd. by comparing \dot{V}_{O_2} during cycling ergometer measured using the snorkel and a standard face mask, and reported that the respiratory snorkel was highly accurate, which was supported by the R² value of 0.994-0.998, and acceptable Passing-Bablok regression

equation parameters (slope value: from 1.001 to 1.006, intercept value: from -1.628 to -6.126).

In swimming research, $\dot{V}O_2$ has been investigated using the combination K4b² system and respiratory snorkel, especially in front crawl (Figueiredo, Toussaint, Vilas-Boas, & Fernandes, 2013; Figueiredo, Zamparro, et al., 2011; Komar et al., 2012; Seifert, Komar, et al., 2010; Zamparro, Bonifazi, et al., 2005; Zamparro et al., 2000). However, there have been few studies in which swimmer's $\dot{V}O_2$ during back crawl were measured using these apparatus. There have also been few studies in which the difference in swimmer's $\dot{V}O_2$ between front crawl and back crawl was assessed.

2.3.3.2. Anaerobic Energy Expenditure Measurement in Swimming

To measure \dot{E} and C above the anaerobic threshold in swimming, $\dot{V}O_2$ and blood lactate values have been used as indicators of aerobic and anaerobic energy expenditure respectively. In the 1960s, Margaria, Cerretelli, Diprampero, Massari, & Torelli (1963) and Margaria, Cerretelli, & Mangili (1964) used blood lactate values to estimate the total \dot{E} in running, and Di Prampero et al. (1978) applied the same method to \dot{E} measurement in swimming. In the study of Di Prampero, it was concluded that the energy released by anaerobic glycolysis can be estimated using the energy equivalent for lactate accumulation in the blood ($2.7 \text{ ml } O_2 \cdot \text{mM}^{-1} \cdot \text{kg}^{-1}$). This method has been used widely to assess anaerobic \dot{E} of swimmers (Barbosa et al., 2008; Fernandes, Billat, et al., 2006; Figueiredo, Barbosa, et al., 2012; Figueiredo, Zamparro, et al., 2011). Using this method, Barbosa et al. (2006) compared \dot{E} between each competitive stroke, and showed that \dot{E} in back crawl was significantly higher than that in front crawl at the swimming speeds of 1.0, 1.2, and 1.4 $\text{m} \cdot \text{s}^{-1}$, but there

was no difference in \dot{E} between the strokes at the speed of $1.6 \text{ m}\cdot\text{s}^{-1}$. However, the results of \dot{E} in front crawl and back crawl were based on different groups of swimmers in the study of Barbosa et al. (2006), and thus, there is a possibility that the result contained errors due to the individual physiological differences.

The \dot{E} measurement using blood lactate values enabled swimming researches to assess anaerobic \dot{E} during swimming and provided knowledge about the physiological response of the body at the anaerobic exercise intensity during swimming. However, this method is still in discussion since the blood lactate severely underestimates muscle lactate concentrations (Scott & Kemp, 2005), and the individual differences in the energy equivalent of the lactate accumulation are too large to ignore (Thevelein et al., 1984). In fact, some other swimming studies have used different energy equivalent values for lactate accumulation ($3.3 \text{ ml O}_2\cdot\text{mM}^{-1}\cdot\text{kg}^{-1}$: Zamparo et al., 2000; Zamparo, Bonifazi, et al., 2005). Thus, the accuracy of measuring anaerobic \dot{E} during swimming is still questionable.

2.3.4. Summary of Energy Expenditure Measurement in Swimming

Using both direct and indirect $\dot{V}\text{O}_2$ measurements, several researchers have reported that the aerobic \dot{E} in back crawl is higher than that in front crawl. However, the results of those studies are questionable because of limitations of the methods, such as comparing different groups of swimmers and the use of methods requiring many conditions which cannot be validated.

The development of testing equipment (portable gas analyser, respiratory snorkel and valves) has allowed researchers to assess \dot{E} of swimmers simply and accurately, and

sometimes with other measurements such as 3D motion analysis. However, the difference in \dot{E} between front crawl and back crawl has not yet been compared using these apparatuses.

In recent years, researchers have investigated anaerobic \dot{E} during swimming using blood lactate accumulation. Although this method enabled researchers to investigate \dot{E} during swimming at swimming speeds close to the race speed, the use of anaerobic \dot{E} measurement is still controversial.

Thus, to investigate the physiological difference between front crawl and back crawl, it is necessary to investigate the anaerobic threshold of each swimmer in both front crawl and back crawl prior to \dot{E} measurement to set the aerobic exercise intensity during \dot{E} measurement. It is also important to compare the two strokes performed by the same group of swimmers to avoid possible errors due to individual physiological characteristics. To conduct \dot{E} measurement with 3D motion analysis, which allows researchers to investigate both physiological and biomechanical characteristics of the strokes, it is necessary to use a portable gas analyser, respiratory snorkel and valve so that swimmers can swim at the centre of the pool with least restriction.

2.4. Swimming Efficiency

To consider both physiological and biomechanical differences between front crawl and back crawl, it is necessary to assess the difference in swimming efficiency (η) between the strokes since η is linked to both physiological and biomechanical parameters (Longo et al., 2008; Sanders, 2011).

In swimming, different types of η have been calculated based on the partitioning of mechanical power output into its useful and non-useful components (Zamparo & Swaine,

2012). There have been three types of efficiency which have been used as indexes of swimming efficiency, namely performance (or drag) efficiency (η_D), Froude efficiency (η_F), and the propelling efficiency (η_P).

According to Zamparo et al. (2011, 2002) and Zamparo & Swaine (2012), η_D is the ratio of useful mechanical power output to overcome drag (\dot{W}_D) to metabolic power input (\dot{E}), η_F is the ratio of \dot{W}_D to the power required to overcome external forces (\dot{W}_{EXT}), and η_P is the ratio of \dot{W}_D to the total power output (\dot{W}_{TOT}). The differences between those efficiencies are whether the efficiency with which \dot{W}_{TOT} produced by the swimmer is transformed into \dot{W}_{EXT} (hydraulic efficiency: η_H) and mechanical efficiency (η_O : the ratio of \dot{W}_{TOT} to \dot{E}) are taken into account. Thus, the relationships between each efficiency can be expressed by the following equations (Daniel, 1992; Zamparo et al., 2011; Zamparo, Pendergast, et al., 2005; Zamparo & Swaine, 2012).

$$\eta_P = \eta_F \cdot \eta_H \quad (\text{Equation 2. 1})$$

$$\eta_O = \eta_D \cdot \eta_P^{-1} \quad (\text{Equation 2. 2})$$

And thus,

$$\eta_D = \eta_P \cdot \eta_O \quad (\text{Equation 2. 3})$$

$$\eta_D = \eta_F \cdot \eta_H \cdot \eta_O \quad (\text{Equation 2. 4})$$

To establish accurate relationships between the difference in the physiological difference and the biomechanical difference between front crawl and back crawl, it is necessary to understand the advantage and limitations of assessing each efficiency, and choose appropriate efficiency variables for this study. In the following sub-sections, studies regarding η_D , η_F , and η_P are summarised to explore the advantages and limitations of the use of each efficiency.

2.4.1. Performance (Drag) Efficiency (η_D) in Swimming

Karpovich & Pestrecov (1939) calculated η_D in front crawl and back crawl using \dot{E} and work done in a given distance which was calculated using mathematical models, and reported η_D of 1.0-1.5 % in front crawl (excluding poor swimmers' data) and η_D of 0.88-1.35 % in back crawl. However, the efficiency values in the study of Karpovich & Pestrecov (1939) slightly differed from later studies. Di Prampero et al. (1974) reported slightly higher η_D values (2.61 ± 0.27 % at the swimming speed of $0.55 \text{ m}\cdot\text{s}^{-1}$, and 5.24 ± 0.49 % at the speed of $0.90 \text{ m}\cdot\text{s}^{-1}$) than those in the study of Karpovich and Pestrecov, and concluded that the difference was due to the fact that Karpovich and Pestrecov assumed that active drag during swimming was equal to the passive drag of the swimmer. Pendergast et al. (1977) investigated η_D in front crawl using the same method as the one in the study of Di Prampero et al. (1974) with larger number of the participants and the wider range of the testing speeds. In their study, Pendergast et al. (1977) also showed higher η_D values than those in the study of Karpovich & Pestrecov (and similar values as those in the study of Di Prampero et al.; 2.9 ± 0.2 % at the swimming speed of $0.4 - 0.55 \text{ m}\cdot\text{s}^{-1}$, and 5.0 ± 0.5 % at the speed of $0.8-0.9 \text{ m}\cdot\text{s}^{-1}$).

Although the results of those studies are probably more reliable than the study of Karpovich & Pestrecov in which the difference between passive drag and active drag was neglected, the extrapolation method still has technical limitations. The first limitation is that the underlying assumption of this method that \dot{W}_D is equal to \dot{W}_{TOT} , and thus η_P is 100%, which is not the case (Toussaint, Beelen, et al., 1988). The second limitation is that it is difficult to assess the active drag accurately (see section 2.5.2), and thus, the calculation of the efficiency based on the active drag estimation might produce inaccurate results.

The use of η_D as the indicator of swimming efficiency has the advantage that it is based on the physiological work (usually calculated from $\dot{V}O_2$ values) and the biomechanical work (usually estimated from active drag values), and thus it is easy to establish the direct

relationship between physiological parameters and biomechanical parameters. However, the difficulty of predicting active drag accurately remains an issue when attempting to quantify η_D accurately.

2.4.2. Propelling Efficiency (η_P) and Froude Efficiency (η_F) in Swimming

Toussaint, Beelen, et al. (1988) were the first swimming researchers to suggest the importance of measuring η_P . In their study, it was reported that the portion of kinetic energy, which swimmers transferred to the water but does not produce forward propulsion, cannot be ignored. In the study of Toussaint, Beelen, et al. (1988), the active drag and η_P during arms-only front crawl swimming was estimated using the Measurement of Active Drag System (MAD-system), developed by Hollander et al. (1986), and several regression models. The first step of the method is to assess \dot{W}_{EXT} using the MAD-system (on MAD-system \dot{W}_{EXT} is equal to \dot{W}_D) together with \dot{E} calculated by swimmer's oxygen uptake at a certain speed, and create individual regression models between \dot{E} and \dot{W}_{EXT} . The second step of the method is to measure \dot{E} during free swimming at the same speed as the testing on the MAD-system and calculate \dot{W}_{EXT} using the individual regression models (at this stage, it is assumed that η_H and η_O are the same between the MAD-system swimming and free swimming). The final step is to calculate the efficiency using \dot{W}_D predicted by the MAD-system and \dot{W}_{EXT} calculated by the regression models.

In the study of Toussaint, Beelen, et al. (1988), it was reported that η_P among elite swimmers ranged from 46 to 77%, and η_O in the elite swimmers ranged from 8 to 12%, and thus η_D ($\eta_P \cdot \eta_O$) ranged from 5 to 8%. Toussaint et al. (1991) and Toussaint (1990) applied the same method to calculate η_P to assess the difference in the efficiency between competitive

swimmers and triathletes, and between swimming with and without puddles. In these studies, it was reported that η_P in competitive swimmers was significantly higher than that in triathletes (60.8 vs 43.6 %), and to use paddles (with a surface of 0.026 m²) significantly increased η_P from 63.7 to 69.0%. It should be noted, however, that the efficiency calculated in all those studies is not η_P , but η_F since η_H was not taken into account in the studies (see Equation 2.1). Also, the method using the MAD-system is only applicable for arm-only front crawl (Barbosa, Marinho, Costa, & Silva, 2011), and thus, the efficiency cannot be compared between front crawl and back crawl with this method.

In fact, to calculate η_P is difficult in swimming since the internal work rate (\dot{W}_{INT}), which is power to accelerate body segments which does not directly contribute to a change of the COM position (Minetti, 1998), cannot be measured during swimming (except during swimming with only kick motion, which does not have much forward/backward movements of body segments relative to COM: Zamparo et al., 2002). Zamparo, Pendergast, et al. (2005) measured \dot{W}_{INT} during simulated front crawl motion on land using a swim-bench, and calculated η_P , using η_F measured in free swimming and the \dot{W}_{INT} values which were calculated during the simulated front crawl. It was concluded in the study of Zamparo, Pendergast, et al. (2005) that the contribution of η_H to determining η_P is quite small compared with η_F , and \dot{W}_{INT} of kicking motion is responsible for the difference between η_P and η_F .

Because of the difficulty of measuring \dot{W}_{INT} during swimming, and since η_F is the primary factor which determines η_P , researchers often calculate η_F as an indicator of swimming efficiency. In recent years, η_F during swimming has been calculated using kinematic variables such as SF , swimming speed, and 3D hand speed. Zamparo, Pendergast, et al. (2005) developed a mathematical model to calculate η_F in front crawl (Equation 2.5) which was based on a model originally proposed by Martin, Yeater, & White (1981). In the model,

it was assumed that the upper limbs are rigid segments of length L , and rotating at constant angular velocity about the shoulder joints.

$$\eta_F = (v \cdot (2\pi \cdot SF \cdot L)^{-1})(2 \cdot \pi^{-1}) \quad (\text{Equation 2. 5})$$

Since the effect of propulsion by kicking is not taken into account in Equation 2.5, the equation is sometimes modified to Equation 2.6 to calculate the η_F of the arm stroke.

$$\eta_F = ((v0.9) \cdot (2\pi \cdot SF \cdot L)^{-1})(2 \cdot \pi^{-1}) \quad (\text{Equation 2. 6})$$

Zamparo (2006) used the model (Equation 2.6) to assess the difference in η_F among a wide age range (from 11 to 54 years old) and gender of swimmers, and showed that the highest value of η_F in the group was among those aged 16, and no difference in η_F between males and females. From the result, Zamparo (2006) attributed the differences in the energy cost (C) between males and females to differences in resistive forces, since C in swimming depends on η_F and resistive forces.

The models of Zamparo, Pendergast, et al. (2005) is based on the theory that the efficiency of the rowing or swimming with oar-motion can be expressed by the following equation (Alexander, 1968; 2003),

$$\eta_F = (v \cdot u^{-1})((d - d') \cdot (d + d')^{-1}) \quad (\text{Equation 2. 7})$$

Where v is the speed of the boat/body, u is the speed of the oar during the stroke cycle, d is resistive forces acting on the oar during the power phase (which is underwater phase in swimming), and d' is the resistive forces acting on the oar during the recovery phase. In swimming (except breast stroke), the upper limbs do not encounter resistive forces from the water during the recovery phase ($d' = 0$), and thus, Equation 2.7 can be transformed into Equation 2.8 for swimming research except for breaststroke studies.

$$\eta_F = v \cdot u^{-1} \quad (\text{Equation 2. 8})$$

In the mathematical model of Zamparo, Pendergast, et al. (2005), the speed of the oar (hand) is calculated using SF with an assumption being that the upper limbs are rigid segments of length L , and rotating at constant angular velocity about the shoulder joints.

Although the model has an advantage that it can calculate η_F using simple variables, it has several limitations. The first limitation is that the assumption of upper limbs being rotating at constant angular velocity about the shoulder joints. However, swimmer's hand speed is in fact not constant during the stroke cycle (Counsilman, 1981). The second limitation is that the upper limbs are also assumed to be rigid segments with certain length. This is also not the case considering the elbow joint angle varies during the stroke cycle (McCabe et al., 2011, 2015; McCabe & Sanders, 2012). The third limitation is that the efficiency theory of Alexander (1968, 2003), which the mathematical model of Zamparo, Pendergast, et al. (2005) is based on, does not reflect the acceleration and deceleration of the boat, and thus, the model of Zamparo, Pendergast, et al. (2005) also cannot reflect the effect of the acceleration and deceleration of the swimmer.

Figueiredo, Zamparo, et al. (2011) applied the theory of Alexander (1968; 2003) in a different approach to calculate η_F during swimming. The authors used 3D mean hand speed relative to COM as u in Equation 8 in his study (Equation 2.9)

$$\eta_F = v_{COM} \cdot 3Du^{-1} \quad (\text{Equation 2. 9})$$

Where v_{COM} is mean COM speed during the stroke cycle, and $3Du$ is the 3D hand speed relative to COM during the stroke cycle. Figueiredo, Zamparo, et al. (2011) compared η_F calculated by Equation 2.5 and that calculated by Equation 2.9 and reported that η_F calculated by the two equations were positively correlated ($r=0.44$, $p<0.01$). Although this method also has similar limitations as the mathematical model of Zamparo, Pendergast, et al. (2005), such as the assumption of constant velocity of the body, or ignorance of the energy loss due to the sideways motion of the body, this method has advantages that it can be

applicable for both front crawl and back crawl, and it can be calculated from kinematic variables. Another advantage of calculating η_F using 3D hand speed is that it is possible to investigate how much each stroke phase contributes to η_F because 3D hand speed during the stroke cycle is determined by the relative duration (the duration in relation to the total stroke cycle time) and 3D hand speed during each stroke phase (Equation 2.10)

$$3Du_{SC} = \frac{3Du_{Entry} \cdot d_{Entry}}{t_{SC}} + \frac{3Du_{Pull} \cdot d_{Pull}}{t_{SC}} + \frac{3Du_{Push} \cdot d_{Push}}{t_{SC}} + \frac{3Du_{Release} \cdot d_{Release}}{t_{SC}} + \frac{3Du_{AWater} \cdot d_{AWater}}{t_{SC}}$$

(Equation 2. 10)

Where $3Du_{SD}$ is the mean 3D hand speed during the stroke cycle, $3Du_{phase}$ is the mean 3D hand speed during each phase ($m \cdot s^{-1}$), t_{phase} is the duration of each phase (seconds), and t_{SC} is the duration of the stroke cycle (seconds). Equation 2.9 and Equation 2.10 suggest that at a given swimming speed, a phase which has short relative duration or slow 3D hand speed contribute to produce low η_F . There have been no study in which the contribution of each phase on η_F is discussed. However, it is important to investigate the relationship between η_F and each stroke phase to explore which phase and motion in that phase positively or negatively contribute to produce high or low η_F in swimming.

2.4.3. Summary of Efficiency Measurements in Swimming

η_D , η_P , and η_F have been measured as indicators of swimming efficiency. Considering that η_D cannot reflect the effect of internal work and kinetic energy the hand gives to the water (Toussaint, Beelen, et al., 1988), η_P , and η_F are better indicators for swimming efficiency than η_D . Given that η_P is difficult to measure since internal work of the upper limbs during swimming cannot be measured, and the effect of the internal work is negligible for

measuring swimming efficiency (Zamparo, 2006), η_F is currently the most reliable method to calculate the efficiency. Considering the MAD-system, which has been used to assess η_F in front crawl, can only be applied for arm-only front crawl swimming, mathematical models based on the theory of oar-motion efficiency (Alexander, 1968; 2003), is the most appropriate way to calculate η_F in different strokes.

After the comparison in η_D between front crawl and back crawl by Karpovich & Pestrecov (1939), no attempt has been made to compare the efficiency between front crawl and back crawl. Although Karpovich & Pestrecov reported slightly higher η_D values in front crawl than in back crawl, the accuracy of the results is questionable since it was assumed that the active drag during swimming was equal to passive drag in the calculation, which is not the case. Also, in the study of Karpovich & Pestrecov, data of different groups of swimmers were used to calculate the efficiency of front crawl and back crawl. Considering that the efficiency is influenced by anthropometric characteristics of the swimmer, it is necessary to compare the efficiency between the strokes using data from the same swimmers.

Thus, the most appropriate way to calculate η_F in front crawl and back crawl of the same group of swimmers is to use COM speed and the 3D mean hand speed in accordance with Figueiredo, Zamparo, et al. (2011).

2.5. Forces in Swimming

Swimming performance is determined by the forces swimmers experience in the water, i.e. propulsive forces and resistive forces (E. Maglischo, 2003), since these forces affect primary factors in swimming, such as SL , E , C , and η . Thus, to compare front crawl and back crawl, it is necessary to consider the differences in the forces between front crawl and back crawl,

even though the direct measurement of the force during swimming is difficult. Methods for direct measurement of propulsive and resistive forces which are produced by, and act on, the whole body of swimmers during free swimming have not yet been established. However, it has been of great interest to assess these forces during swimming and both propulsive and resistive forces have been investigated with some assumptions and/or limited experimental conditions. In this section, methods used for assessing propulsive forces and resistive forces and their limitations are summarised in the following sub-sections to consider the most appropriate way to assess the differences in forces between front crawl and back crawl.

2.5.1. Propulsive Forces in Swimming

2.5.1.1. Propulsive Drag and Lift Forces

Propulsion in swimming is generated by propulsive drag and lift forces which swimmers' limbs produce in the water (E. Maglischo, 2003). The propulsive drag force theory is based on Newton's third law of motion – when the swimmer pushes the water backward with his/her upper limbs, the swimmer was driven forward by the reaction force (Counsilman, 1968). The lift force theory was proposed by Brown & Counsilman (1971) when they observed lateral and vertical hand motion during swimming by analysing film. The lift force theory has mostly been based on Bernoulli's theorem – when swimmers sweep their hand with optimal angle of attacks, the pressure distribution differs between the front and back of the hand. The lift force is used as a force resisting backward hand movement when the shoulder muscles shortened i.e. lift forces help the hand to be fixed in the water so that the body would be moved forward relative to the hand and the water when the shoulder extends or adducts (Barthels, 1979). Theoretically, both propulsive drag and lift forces are in proportion to the square of the speed of the flow (Alexander, 1968; Equation 2.12 and 2.13)

$$F_D = 0.5\rho u^2 AC_D \quad (\text{Equation 2. 11})$$

$$F_L = 0.5\rho u^2 AC_L \quad (\text{Equation 2. 12})$$

Where F_D and F_L are propulsive drag and lift forces respectively, ρ is the density of the water, u is the velocity of the water relative to the hand, A is a surface area of the hand, and C_D and C_L are drag and lift coefficients respectively. It has been reported that C_D is much larger than C_L during swimming motion (Berger, De Groot, & Hollander, 1995), on the other hand, it has also been reported that the lift force is beneficial because of the relative small energy loss to the water (Berger, Hollander, & De Groot, 1997).

It has been controversial whether lift or drag force is the primary contribution to propulsive force, however, the importance of drag force has been emphasised over lift force in recent years (E. Maglischo, 2003). Ferrell, Hendrick, & McGinnis (1993) investigated the water flow around the hand model and concluded that lift forces are not important components for hand propulsion in swimming, since the flow around the hand model is predominantly turbulent, rather than laminar flow which is the underlying assumption of the lift-force theory based on Bernoulli's principle. Toussaint, Van den Berg, & Beek (2002) and Toussaint (2000) conducted experimental studies to assess the water flow around the hand and upper limbs during front crawl using black woollen tufts, and verified the result of Ferrell's study. Bixler & Riewald (2002) investigated the water flow around the swimmer's hand and forearm model using computational fluid dynamics (CFD), and found that the boundary layer of the flow did not remain attached on the model, and also found that the drag coefficients the model produced exceeded the lift coefficients at all angles of attack. Nevertheless, these findings do not necessarily mean that the contribution of the lift force on the propulsion is negligible. These studies simply suggested that the lift force could not be generated by Bernoulli's principle in swimming. In fact, Kudo et al. (2012) reported that the propulsive lift force increased with the increase in the vertical-lateral hand speeds in front

crawl. Kudo et al. (2012) only investigated three swimmers, and thus, the result cannot be generalised, however, the possible importance of the hand speed in vertical-lateral directions to produce the propulsive lift force should be recognised.

It is difficult to calculate accurate forces using the equations since determining C_D and C_L are difficult. However, hand speed and acceleration have been considered as important kinematic factors for producing large propulsive force in swimming since propulsive drag and lift forces is in proportion to the square of the hand speed (Equation 2.12, and Equation 2.13), and the propulsive drag force the hand of the swimmer produces also depends on the hand acceleration (Counsilman, 1981). In the next sub-section, studies in which hand speed and/or acceleration during swimming were investigated are summarised.

2.5.1.2. Hand Speed and Acceleration in Swimming

Since the drag and lift forces depend on square of the hand speed (Equation 2.10, and Equation 2.11) and the hand acceleration is related to added mass effect (an effective mass of water is accelerated, thereby yielding additional forces) and vortex shedding effect (shedding of vortices produces some unsteadiness in forces), it has been considered that hand speed and acceleration are factors which determine the propulsive force produced by the hand (Pai & Hay, 1988; Sanders, 1999). Several researchers have investigated hand speed and hand acceleration of the swimmer. Counsilman (1981) conducted a testing to measure the hand kinematics of 3 international swimmers and 3 'poor swimmers' swimming in a calibrated space using two movie cameras (filmed from the underneath and the side of swimmers). It was reported that the international swimmers had faster hand speed and larger hand acceleration than poor swimmers although the acceleration pattern was similar (Counsilman, 1981), which suggests that skilled swimmers apply larger mean propulsive force to the water

during the stroke cycle than non-skilled swimmers. Kudo et al., (2012) estimated the propulsive drag and lift forces produced by swimmer's hand during front crawl using a total of twelve pressure sensors, and reported that the propulsive drag and lift forces by competitive swimmer's hand were in proportion to the square of the hand velocity in the swimming direction ($R^2=0.93-0.97$), and vertical-lateral directions ($R^2=0.65-0.96$) respectively. It should be noted, however, that Kudo et al., (2012) only investigated three swimmers (including two triathletes), and thus, it is questionable that the results can be generalised for competitive swimmers. Yet, theoretically it is logical that the hand speeds in the swimming, vertical and lateral directions are important to produce propulsive drag and lift forces (Equation 2.12, and Equation 2.13), and the importance of the hand speed in the three directions should be recognised in swimming researches. Kudo, Vennell, & Wilson (2013) investigated the effect of hand acceleration on drag and lift forces produced by the hand using a robotic hand model and a tri-axial load cell and reported that the propulsive force produced by an accelerating hand is up to 3.8 times larger than that produced by a non-accelerating hand. In the study of Kudo et al. (2013), it was also reported that even hand deceleration produced larger propulsive force than non-accelerating/decelerating hand, and thus hand deceleration also gives positive contribution to producing large propulsive force. It should be noted that the robotic arm movement in the study of Kudo et al. (2013) was very simplified. In the study, the arm movement only consisted of angular backward motion of the hand and did not include any other movements swimmers actually applied in the water such as elbow flexion or internal and external rotations of shoulder. Nevertheless, the relationships between the hand model acceleration and deceleration and hydrodynamic forces are still worth to consider as possible effects of hand acceleration and deceleration on producing propulsive forces in swimming.

Pai & Hay (1988) suggested that several hydrodynamic factors (such as the vortex shedding effect in the water) have huge effect on determining C_D and C_L , and that quasi-static analysis

cannot calculate accurate propulsive forces in swimming. Nevertheless, hand speed and acceleration are still important factors which determine propulsive forces considering the strong correlation between the hand speed/acceleration and the propulsive force in above mentioned studies. Although hand speed/acceleration/deceleration of the swimmer in front crawl have been investigated, no study has been conducted to assess those characteristics in back crawl. Even though hand kinematics are not sufficient factors to calculate the whole propulsive forces in swimming, it is necessary to compare the hand kinematics between front crawl and back crawl to predict the difference in propulsive forces produced by the hand between the two strokes.

2.5.2. Resistive Forces in Swimming

2.5.2.1. Overview of Resistive Force Measurement in Swimming

Resistive force, which is often called ‘active drag’ in swimming, is the force component which acts opposite direction of the swimmer’s movement, and causes deceleration of the swimmer. It is difficult to assess the resistive force in swimming due to controversy surrounding the ability to measure the force (Sacilotto, Ball, & Mason, 2014). Yet, several methods and instruments to assess resistive forces have been proposed in the last decades. Di Prampero et al. (1974) developed a method to estimate the resistive force in swimming using an energetics approach. In this approach, swimmers are required to swim at a set pace with known additional weight for adding/subtracting extra loads to/from swimmers swimming at a known speed. $\dot{V}O_2$ was also measured during the assisted/resisted swimming to assess swimmers’ energy expenditure. The linear relationship between the extra resistive/assistive forces and $\dot{V}O_2$ was identified to determine the resistive force as a function

of $\dot{V}O_2$. This method was applied in a study by Pendergast et al. (1977) who investigated the difference in resistive force between male and female swimmers, and showed significantly smaller resistive force in female than male swimmers. Although this approach was the first attempt to measure the resistive force while swimming actively, and thus gave huge impact on swimming research, this method has several limitations. The first limitation is that it was assumed that the propelling efficiency remains the same when the swimming speed increases or decreases, which is not the case (see Section 2.4). The second limitation is that it was assumed that the swimming speed is constant and the fluctuation of the speed during the stroke cycle was not taken into account.

The MAD-system (see Section 2.4.2) has been one of the most popular equipment to investigate the resistive force in swimming. The system consists of fixed pads which are mounted on a rod of 23m length, and a force transducer connected to the rod. Swimmers push each pad while moving forward with arm-only front crawl motion (so that the legs do not contribute to propulsion) in the water. The push-off force is measured by the system, and under the assumption that the swimming velocity is constant, the resistive force is assumed to be the same as the measured push-off force. The trial to estimate the resistive force is usually repeated at different swimming velocities, and a least squares curve fit is applied to the equation

$$D = A \cdot v^n \quad (\text{Equation 2. 13})$$

Where D is the estimated mean active drag (mean push-off force), v is the swimming speed corresponds to the mean active drag, and A and n are constants of proportionality (Toussaint, Roos, & Kolmogorov, 2004; Toussaint, Savelberg, & Hollander, 1988).

The system has been used extensively to estimate the resistive force in swimming (Formosa, Toussaint, Mason, & Burkett, 2012; Seifert, Toussaint, et al., 2010; Toussaint, Truijens, et al., 2002; Toussaint et al., 1990, 2004; Van der Vaart et al., 1987). However, there is much

criticism regarding the limitations of this technique. The first concern is that the mechanism of generating the force using the MAD-system differs from actual swimming in which the swimmer pushes the water instead of fixed plates (Poizat, Ade, Seifert, Toussaint, & Gal-Petitfaux, 2010; Sanders et al., 2012). The second concern is that the MAD-system is only applicable for front crawl with arm-only and thus the effect of the kick is not taken into account (Barbosa et al., 2011). The third concern is that it is assumed that the swimmer does not produce any propulsive force during the period from the hand entry to the start of pad-pushing (Xin-Feng, Lian-Ze, Wei-Xing, De-Jian, & Xiong, 2007).

Another method for measuring swimmer's resistive force is the velocity perturbation method (VPM) which was proposed by Kolmogorov & Duplishcheva (1992). This method requires swimmers to perform 20 – 30m maximal effort swimming trials with and without a hydrodynamic body which creates a known additional resistive force, and with assumptions that the power output of the swimmer is maximal and equal between the trials using the following equation

$$D_f \cdot v_f = (D_t + F_b) \cdot v_t \quad (\text{Equation 2. 14})$$

Where D_f is the resistive force the swimmer obtains in the maximal free swimming trial, v_f is the swimming speed of the maximal free swimming trial, F_b is the additional resistance of the hydrodynamic body, D_t is the resistive force the swimmer obtains in the maximal swimming trial with the hydrodynamic body, and v_t is the swimming speed of the maximal swimming trial with the hydrodynamic body. Using Equation 2.12, Equation 2.15 can be converted into the following equation.

$$0.5 \cdot \rho \cdot A \cdot C_D \cdot v_f^3 = 0.5 \cdot \rho \cdot A \cdot C_D \cdot v_t^3 + F_b \cdot v_t \quad (\text{Equation 2. 15})$$

And thus,

$$C_D = \frac{F_b \cdot v_t}{0.5 \cdot \rho \cdot A \cdot (v_f^3 - v_t^3)} \quad (\text{Equation 2. 16})$$

Again using Equation 2.12, Equation 2.17 is converted into the following equation which gives the resistive force (D) of the swimmer during maximum swimming.

$$D = \frac{F_b \cdot v_t \cdot v_f^2}{v_f^3 - v_t^3} \quad (\text{Equation 2. 17})$$

This method has an advantage over the other methods (energetics approach and MAD-system) since it allows researchers to measure the resistive force in all four swimming strokes without restricting kick motion, and it does not require huge instruments for the measurement (Sacilotto et al., 2014). However, this method also has its limitations. The first limitation is that the resistive force during only maximal effort swimming can be assessed with this method (Mason, Sacilotto, & Menzies, 2011). The second limitation is the underlying assumption of the equal power output of the swimmer between the trials with and without a hydrodynamic body, which is questionable (Toussaint et al., 2004). The third limitation is that the intra-cycle velocity fluctuation and the resistive force fluctuation are not quantified in this method (Sanders et al., 2012). The use of the mean swimming speed also leads to the fourth limitation, which is the error related to the use of the square and the cubic of the swimming speed in the equation (Equation 2.18). For example, only 5% error in the swimming velocity corresponds to more than 15% error in the cubic of the swimming velocity, and considering the potential risk of producing huge error in the calculation, the accuracy of VPM method is questionable.

In recent years, another technique for measuring the resistive force in swimming (Assisted Towing Method: ATM) has been introduced by Alcock & Mason (2007). The basic theory and process of assessing the resistive force using ATM are quite similar to those of VPM, except that the swimmer is assisted in ATM, rather than resisted. The advantage of ATM over VPM is that it is possible to reflect the force fluctuation during the stroke cycle since the assisted force is constantly measured in this method. However, similar to VPM, the resistive force only during maximal effort swimming can be assessed with ATM (Gatta,

Cortesi, Fantozzi, & Zamparo, 2015), and Formosa et al. (2012) showed large differences between the resistive force measured by the MAD-system and that measured by ATM, and thus, the accuracy of this method is still questionable.

Although the resistive force is an important factor to assess swimming performance, it is difficult to measure the resistive force in swimming because of technical limitations such as those described above. For this reason, some researchers have discussed the resistive force using simple kinematic and kinetic variables.

Sanders, Gonjo, & McCabe (2015) suggested that large fluctuations of net force, which is sum of propulsive and resistive forces, reflects the large resistive force acting on the swimmer. Net force is a product of COM acceleration and body mass of the swimmer, and thus, it is a useful variable which can be obtained by kinematic analysis. It would also be useful to calculate the net impulse during the propulsive phases (pull and push phases) to obtain detailed information regarding the propulsive net force exerted over the duration of each stroke phase. However, it should be noted that COM acceleration is the second derivative of the COM displacement data and is sensitive to error (Sanders, Gonjo, et al., 2015). Therefore, the reliability error on these variables should be calculated before the data is used for the argument.

Velocity fluctuation of COM (Intra-cycle Velocity Variation; *IVV*) can be an indicator of relative resistive (or propulsive) forces (Vilas-Boas, Fernandes, & Barbosa, 2011). In the next section, literature related to *IVV* in swimming are summarised.

2.5.2.2. *IVV* in Swimming

Since *IVV* is a variable which reflects the balance of propulsive and resistive forces during the stroke cycle, it is necessary to compare *IVV* between front crawl and back crawl to consider the difference in the force balance between the strokes. In this section, literature regarding *IVV* are summarised to consider the appropriate method and its limitations of measuring *IVV* in front crawl and back crawl in this study.

Barbosa et al. (2013) suggested that *IVV* is dependent on the applied net force, and thus *IVV* can be an indicator of relative propulsive and resistive forces. In fact, Barbosa et al. (2013) concluded that there were significant correlations between the resistive force and *IVV* when the effect of swimming speed is controlled in young male and female groups (young male: $r=0.72$, $p=0.03$, young female: $r=0.84$, $p=0.02$).

IVV has been obtained using either data from video images (Alves et al., 1996; Barbosa et al., 2005; Barbosa, Lima, et al., 2006; Psycharakis et al., 2010; Psycharakis & Sanders, 2009) or a purpose made-device which usually consists of tachometer (speed meter) with a cable (Alberty, Sidney, Huot-Marchand, Hespel, & Pelayo, 2005; Craig & Pendergast, 1979; Payton & Wilcox, 2006; Sidney, Paillette, Hespel, Chollet, & Pelayo, 2001). 2D or 3D motion analysis have been commonly used to obtain *IVV* from data based on video images.

To date, two studies have focused on the difference in *IVV* in front crawl and back crawl using these methods. Alves et al. (1996) compared *IVV* between front crawl and back crawl by assessing *IVV* of the hip using 2D motion analysis derived from a video camera, and concluded that swimmers had larger *IVV* in back crawl than that in front crawl, although the authors did not reported any numerical results. Using the purpose-made device, Craig & Pendergast, (1979) investigated *IVV* in the four swimming strokes and concluded that the intra-cycle minimal velocity (IV_{min}) in back crawl was slightly farther from the mean swimming speed than intra-cycle maximal velocity (IV_{max}), while that in front crawl was

symmetrical, which indicates the possibility that there was (or were) point(s) when the swimmer experienced large resistive force that caused low IV_{min} . The authors explained that low IV_{min} was possibly caused by the flexion of the knee (foot-drop) which produced sudden deceleration of the body.

However, it should be noted that these studies had methodological limitations. In the study of Alves et al (1996), IVV of the hip was calculated rather than IVV of COM. It has been reported that it is not appropriate to use hip joints to calculate IVV since to use hip joint instead of COM would underestimate IVV (Figueiredo et al., 2009; Psycharakis & Sanders, 2009). In the study of Craig & Pendergast, a wire device was used to record IVV of the swimmer, and this type of device has often been used to assess IVV of the swimmer (Alberty et al., 2005; Payton & Wilcox, 2006; Sidney et al., 2001). Since these devices record the fluctuation of the velocity of a certain point or joint on which the wire is attached, there is a concern that the devices do not reflect exact fluctuation of COM velocity (Craig & Pendergast, 1979). The use of 2D motion analysis to calculate IVV of COM also has its limitation since 2D motion analysis cannot reflect the effect of technical asymmetries of swimmers (Psycharakis et al., 2010). And thus, to overcome these concerns and produce more accurate results than the previous studies, it is necessary to compare IVV of COM in front crawl and back crawl using 3D motion analysis.

In addition to the different methods to obtain the data, there have been several ways to assess IVV in swimming.

The first way is to assess the intra-cycle minimal velocity (IV_{min}) and the intra-cycle maximal velocity (IV_{max}) during the stroke cycle (Payton & Wilcox, 2006; Psycharakis et al., 2010; Psycharakis & Sanders, 2009; Sidney et al., 2001). Psycharakis & Sanders (2009) investigated if the hip intra-cycle velocity represented the intra-cycle velocity of COM and concluded maximum hip velocity was larger than IV_{max} and minimum hip velocity was smaller than IV_{min} and thus, the use of hip joint as an indicator of IVV of COM was inaccurate

method. Psycharakis et al. (2010) investigated the effect of *IVV* on 200m front crawl performance and reported that within-participants *IVV* was not associated with swimming performance during 200m front crawl. However, the authors also suggested the importance of identifying differences in kinematic characteristics and *IVV* at a given mean COM speed to investigate effective techniques, in other words, differences in technique between swimmers. Given that front crawl and back crawl have similar alternative stroke motion and six beat kicking motion (E. Maglischo, 2003), it is worth to explore the difference in *IVV* between front crawl and back crawl at the same swimming speed to assess the effect of kinematic differences on the performance between front crawl and back crawl. Even though this method cannot reflect the overall speed fluctuation during the stroke cycle, *IVV* calculation based on IV_{max} and IV_{min} is still useful because IV_{max} and IV_{min} reflect the phases where swimmers achieve largest and smallest net impulse during the stroke cycle respectively.

The second method of investigating *IVV* is to use the coefficient of variation (*CV*) of the swimming speed during the stroke cycle (Barbosa et al., 2005; Barbosa, Lima, et al., 2006; Figueiredo, Barbosa, et al., 2012; Figueiredo, Kjendlie, et al., 2012; Seifert, Toussaint, et al., 2010). Using this method, the relationship between the energy cost (*C*) and *IVV* in both front crawl and back crawl was investigated by Barbosa, Lima, et al. (2006) in which it was concluded that there were significant correlations between *C* and *IVV* in both front crawl ($r=0.62$, $p<0.01$) and back crawl ($r=0.55$, $p<0.01$). However, using the same calculation, Figueiredo, Barbosa, et al. (2012) showed opposite result in front crawl ($r=-0.34$, $p<0.05$). The first reason of this contradiction may be a difference in *C* calculation. Barbosa, Lima, et al. (2006) calculated *C* normalised by the body mass ($J \cdot kg^{-1} \cdot m^{-1}$), whereas Figueiredo, Barbosa, et al. (2012) used absolute *C* value ($kJ \cdot m^{-1}$) for the analysis. Since the energy cost depends on swimmer's size and mass (Schmidt-Nielsen, 1971), the result of Figueiredo, Barbosa, et al. (2012) might have been biased by individual differences between the body

mass of tested swimmers. Another possible reason of the difference in the results of the two studies might have been caused by an issue of the *IVV* calculation using *CV*. *CV* is supposed to be used to compare the variables which increase or decrease standard deviation (*SD*) values proportionally as the mean values increase or decrease (Reed, Lynn, & Meade, 2002) otherwise it underestimates the variation of variables if the mean value is large. Although this *IVV* calculation has been widely used, considering that Psycharakis et al., (2010) reported low and no significant correlations between the horizontal *IVV* (calculated by subtracting IV_{\min} from IV_{\max}) and swimming speed, the accuracy of calculating *IVV* using the mean and *SD* of the swimming speed during the stroke cycle is questionable since it probably has the tendency of producing smaller *IVV* in fast swimming trial than in slow swimming trial. In fact, Figueiredo, Kjendlie, et al. (2012) reported a negative correlation between horizontal swimming speed and horizontal *IVV* (calculated using *CV*), which is reasonable considering the above-mentioned matter of using *CV* for calculating *IVV*. Another issue of calculating *IVV* using *CV* is inaccuracy in calculating *IVV* in vertical and lateral directions. *IVV* in vertical direction should not be calculated using *CV* because theoretically the mean COM speed in vertical direction during stroke cycle should be zero, otherwise swimmers would constantly keep rising their body from the water or keep sinking their body in the water. The mean COM speed in lateral direction should also be zero (or nearly zero) if the swimmer successfully swims straight in the lane. In other words, extremely large *IVV* in lateral direction (based on *CV* calculation) would be produced when swimmers swim as straight as possible during the stroke cycle because in that way the mean lateral COM speed becomes nearly zero. Although Figueiredo, Kjendlie, et al., (2012) reported that there were significant negative correlation between IVV_x and SL ($r=-0.37$, $p=0.04$), between IVV_x and SF ($r=-0.34$, $p=0.05$), and between IVV_z and SL ($r=-0.47$, $p=0.01$), considering aforementioned issues, the accuracy of these results are questionable.

The third method of calculation *IVV* is to use an index of velocity fluctuation (*IVF*) which has been used for *IVV* investigation during breaststroke (Leblanc, Seifert, Tourny-Chollet, & Chollet, 2007; Vilas-Boas, 1996). *IVF* is calculated using the equation below

$$IVF = \frac{V_{mean}}{(V_2 - V_1) + (V_4 - V_3)} \quad (\text{Equation 2. 18})$$

Where V_{mean} is the mean swimming speed during the stroke cycle, V_1 is the minimum velocity during the lag time between the propulsive motion of the legs and propulsive motion of the arms, V_2 is the maximum velocity during the propulsive motion of the legs, V_3 is the minimum velocity during the recovery phase of the arms and legs, and V_4 is the maximum velocity during the propulsive motion of the arms. This method has an advantage that the equation reflects primary peaks during the stroke cycle, not only the maximum and minimum peaks during the entire stroke cycle such as the method used by Psycharakis et al. (2010) and Psycharakis & Sanders (2009). However, this method is only applicable for breaststroke *IVV* analysis in which the arm and leg propulsive phase can be clearly identified respectively. For front crawl and back crawl, where swimmers constantly repeat the kick motion during the stroke cycle, it is difficult to distinguish arm and leg propulsive phases, and thus, the use of *IVF* for *IVV* investigation is also difficult.

In summary, it is important to compare *IVV* between front crawl and back crawl using COM speed obtained by 3D motion analysis. Although there have been several methods to investigate swimmer's *IVV*, considering the issues of using *CV* as an indicator of *IVV* in swimming, and the difficulty of calculating *IVF* in front crawl and back crawl, the most appropriate way to assess *IVV* in front crawl and back crawl is to differentiate IV_{min} from IV_{max} . Even though this method cannot reflect overall fluctuation of the swimming speed during the stroke cycle, to use IV_{max} and IV_{min} is still beneficial because IV_{max} and IV_{min} reflect

the phases where the swimmer has the largest and smallest net impulse during the stroke cycle.

2.6. Body Roll in Swimming

Body roll is the angular motion of the trunk (shoulder and hip segments) about the long axis of the body, which is observed in front crawl and back crawl. Many authors suggested the importance of body roll in several ways, and thus, it is important to compare body roll between front crawl and back crawl and its effect on the difference in the swimming performance between the strokes.

The first possible effect of the body roll is to increase/decrease the propulsive force produced by the upper limbs. Hay, Liu, & Andrews (1993) investigated the effect of body roll on hand path in medial-lateral direction using a mathematical model and reported that the greater the body roll, the greater the medial-lateral deviation of the hand and the swimmer should move their hand laterally away from the midline of the trunk to produce the desired medial deviation of the hand. Payton, Hay, & Mullineaux (1997) investigated the effect of body roll on the hand speed using an improved model of Hay et al. (1993), and concluded that the increase in body roll angle at a given pull duration produces larger angular body roll speed, and thus contributes to the increase of sculling speed of the hand. However, in a later experimental study, Payton et al. (2002) and Payton, Bartlett, Baltzopoulos, & Coombs (1999) conducted experimental studies and opposed these results. Payton et al. (2002) and Payton et al. (1999) concluded that the conflict in the results between these studies were due to inaccuracy of the model used in the studies by Hay et al. (1993), Liu et al. (1993), and Payton et al. (1997) in which several assumptions were made including

- The trunk keeps rolling away from the neutral position for the duration of the insweep phase
- The arm rotates laterally relative to the rolling trunk throughout the insweep phase
- The shoulder, elbow and wrist of the swimmer remain in a plane perpendicular to the sagittal plane during the pull

Which are all not the case. Nevertheless, even though the contribution of the body roll to the medial-lateral hand displacement and speed during the insweep phase were negative, it is still possible that the body roll affects to the hand displacement and speed in other phases – namely downsweep and upsweep phases in front crawl, and the hand displacement and speed in back crawl, considering that larger body roll angle makes the lateral displacement of the shoulder closer to the mid-line of the body (Figure 2.3).

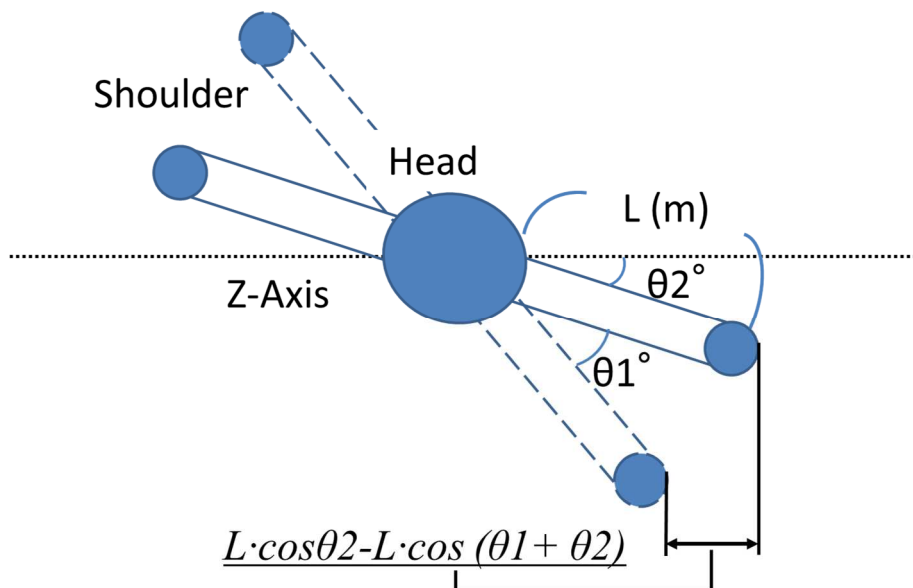


Figure 2. 3: The relationship between shoulder roll angle and the lateral shoulder displacement.

Lecrivain, Payton, Slaouti, & Kennedy (2010) conducted a computational fluid dynamic study to investigate the effect of body roll on propulsive forces produced by the upper arm in an arm amputee swimmer, and reported that the increase in body roll from 0 degrees to 30 degrees increases the propulsion by the upper arm for 51%, and the increase in body roll from 0 degrees to 45 degrees produces 73% more propulsion produced by the upper arm. It should be noted, however, that these studies only focused on front crawl, and no consideration was made for the body roll in back crawl, and there have been limited attempts to investigate the relationship between the body roll angle and the propulsive force produced by the hand.

The second possible effect of the body roll is the influence on the resistive force the swimmer obtains in the water. Clarys & Jiskoot (1975) investigated passive drag in the prone and side (45 degrees roll angle) of the swimmer, and showed significantly less passive drag in the side position than in the prone position at the speed of 1.5 and 1.6 m·s⁻¹. Castro, Minghelli, Floss, & Guimaraes (2003) suggested that one of the important roles of body roll is to prevent undesirable lateral movements during swimming, which would create resistive forces. Although Castro et al. (2003) did not present any evidence which suggested the effect of body roll on the lateral motion of the hand and the body, the possible effect of body roll on lateral motion of the swimmers is reasonable considering the relationship between body roll angle and the displacement of the shoulder (Figure 2.3).

The third possible effect of body roll on swimming performance is its possible relation with *SF*. Yanai (2003) investigated the effect of body roll on *SF* during swimming, and reported a negative relationship between the body roll angle and *SF* in other words, swimmers have to reduce the amount of body roll to obtain higher *SF*. However, in a later study, Psycharakis & Sanders, (2008) reported constant shoulder roll angle during 200m front crawl despite the decrease in *SF*. Psycharakis & Sanders, (2008) concluded the difference was attributed to the difference in the level of swimmers investigated. However, Psycharakis & Sanders (2008)

did not consider the effect of fatigue on the difference between their result and that of Yanai (2003). Considering that SF is not only affected by the body roll, but also by swimmer's internal effort of moving arms (Yanai, 2003), and the primary factor of determining body roll is external fluid force rather than swimmer's internal effort, it is logical that the results by Psycharakis & Sanders (2008) was probably biased by the effect of fatigue which swimmers accumulated throughout the 200m trials. Nevertheless, the difference between these studies raises a suggestion that to assess the effect of body roll on SF , the effect of fatigue should be minimised.

There have also been some studies in which back crawl body roll angle was investigated. Cappaert, Pease, & Troup (1996) conducted 3D motion analysis of back crawl during the race, and highlighted that an elite swimmer rolled her shoulder and hip by the same amount and the timings of the peak shoulder and hip roll were almost the same, on the other hand, non-elite swimmers tended to have opposite rotation from the shoulder and hips. The study by Cappaert et al. (1996) was the first investigation in which shoulder and hip roll angles in back crawl were quantified, and it was meaningful for coaches to know the difference between elite and non-elite swimmers. However, there were two limitations in the study by Cappaert et al. (1996). The first limitation was the possible errors due to the limited number of cameras and the setting of the cameras and manual digitising process without any joint markers. In the study by Cappaert et al. (1996), the motion of the swimmers was recorded from only two cameras from frontal sides, which possibly hindered hip joints to be detected, especially on the side of swimmer's underwater hand stroke being conducted. The possibility of producing errors during manual digitising in these studies was probably also increased by the disuse of joint markers, which probably increased the difficulty of the detection of the hip joints even more. Thus, the accuracy of the hip roll angle in these two studies is questionable. Another limitation is that the highlighted outcome was not based on statistical analysis, and the authors only examined one elite swimmer for the comparison with non-elite

swimmers. Thus, the difference between an elite swimmer and non-elite swimmers might have been due to merely individual characteristics of each swimmer rather than the characteristics of the groups. Alves, Cardoso, Silva, & Veloso, (2004) investigated shoulder and hip roll angles in back crawl of six elite swimmers. It was concluded that the swimmers had similar shoulder roll angle as the participants in the study by Cappaert et al. (1996). However, it was also reported that the maximum hip roll angle was significantly larger than maximum hip roll angle, which conflicted the result of Cappaert et al. (1996). This was probably due to the fact that Cappaert et al. (1996) only investigated one elite swimmer, and thus, the outcome was probably a characteristic of the investigated swimmer, rather than a characteristic of elite swimmers. Nevertheless, the study by Alves et al. (2004) also had two limitations. The first issue was that the investigated group contained both male and female swimmers. Considering that male and female swimmers have different centre of buoyancy location relative to the height (McLean & Hinrichs, 1998), and that buoyancy torque is a factor which generates body roll (Yanai, 2004), it is possible that body roll investigation for a group with mixed gender produces errors. The second limitation was that Alves et al. (2004) also recorded the motion of the swimmers in the water only from two frontal views, and thus it might have produced errors because of the difficulties of hip joints detection as being discussed earlier.

Shoulder and hip rolls (and/or trunk roll, which refers the roll of the whole trunk without differentiate hip and should roll angles) have been investigated by expressing the roll angles relative to the swimming direction (Payton et al., 2002, 1999; Psycharakis & Sanders, 2008; Sanders & Psycharakis, 2009) or by expressing the roll angles relative to the body axis (Alves et al., 2004; Cappaert, Pease, & Troup, 1995; Yanai, 2001, 2003, 2004). The latter way has an advantage that it reflects actual shoulder and hip roll angles the swimmer achieves, whereas the former method has a limitation that the roll angles are slightly simplified because it ignores the effect of the pitch angle of the body. However, considering

that the possible effect of body roll on hand kinematics in medio-lateral plane and the possible effect of body roll on resistive force during swimming which is influenced by the cross sectional area on the plane perpendicular to the swimming direction, it is probably more appropriate to assess shoulder and hip roll angles relative to the swimming direction to investigate the relationship between the roll angles and other kinematic and kinetic variables.

In summary, Although the characteristics of body roll in front crawl (such as the effect of swimming speed on the roll angles) or the effect of body roll on hand kinematics have been assessed, there have been few studies in which back crawl characteristics were assessed accurately. Indeed, Psycharakis & Sanders (2010) emphasised the importance of exploring the body roll characteristics and its effect on the performance in back crawl. Furthermore, considering the possible effect of body roll on propulsive and resistive forces and SF , the differences in body roll between front crawl and back crawl have to be investigated to explore the difference in swimming performance between these strokes. To investigate the difference in body roll angle between front crawl and back crawl and its relation to the difference in swimming performance between the strokes, it is important to assess shoulder and hip roll angles separately by expressing the roll angles relative to the swimming direction.

2.7. Lower Limbs Kinematics during Swimming

It has been reported that the contribution of the leg kicking on the propulsion is much smaller than that of the stroke motion of the upper limbs (Deschodt, Arsac, & Rouard, 1999; E. Maglischo, 2003; Shahbazi-Moghaddam, 2007; Watkins & Gordon, 1982). However, even though the direct contribution of the kick on the propulsion is small, several researchers

have emphasised the importance of leg kicking for swimming performance. The possible effects of leg kicking on swimming performance are

- To change the upper arm stroke trajectory which helps generating larger propulsion than conducting upper arm stroke without kicking (Deschodt et al., 1999)
- To stabilise the body which reduces the resistive forces the swimmer obtains (Shahbazi-Moghaddam, 2007; Watkins & Gordon, 1982)
- To increase the total force production (Morouço, Marinho, Izquierdo, Neiva, & Marques, 2015)
- To reduce the inclination of the body (Gourgoulis et al., 2014), which is caused by the counter-torque produced by the hand (Yanai, 2001)

These proposed effects of leg kicking on swimming performance indicates that the contribution of leg kicking on swimming performance is considered to be indirect but positive. On the other hand, many researchers have reported the evidence of potential risk of energy loss in leg kicking. It has been generally shown that the use of leg kicking in swimming requires greater energy than arms-only swimming (Holmér, 1974; Ogita, Hara, & Tabata, 1996) because leg kick requires activation of larger muscle mass (Di Prampero et al., 1974). McCabe & Sanders (2012) reported that vertical foot displacement ranged from 0.30 to 0.36 m in both sprint and distance swimmers at a distance pace. On the other hand, McCabe et al. (2011) showed vertical displacements of the foot of both sprint and distance swimmers were approximately 0.4 m at a sprint pace, which was larger than the value reported by McCabe & Sanders (2012). This tendency was in agreement with Cappaert (1999) who reported larger range of motion (ROM) of the foot in sprint front crawl events than distance front crawl events. These results are reasonable because in long distance events, swimmers should minimise their energy loss so that they can maintain fast speed throughout the race and thus, to conduct strong kicking is not effective from physiological perspective. Cappaert et al. (1995) and Cappaert (1999) reported similar (approximately 60

degrees) ROM of the foot in back crawl and front crawl at 100 and 200 m events. Similar ROM of the foot indirectly indicated that the energy requirement for leg kicking during front and back crawl is similar considering that identical kicking pattern is used in both front crawl and back crawl (E. Maglischo, 2003). On the other hand, the similar ROM of the foot might indicate that larger resistive force is produced by the leg motion in back crawl than in front crawl. Zamparo, Gatta, Pendergast, & Capelli (2009) suggested that excessive kicking movements may increase the cross sectional area of the swimmer which causes the increase of the resistive force. Considering that the swimmer flexes their knee upward during front crawl kicking, while the flexion of the knee is conducted downward in back crawl kicking, it might be possible that the downward knee flexion in back crawl causes swimmer's shank facing toward the swimming direction more than in front crawl, which possibly increases the resistive force in back crawl. Therefore, it is necessary to investigate the difference in vertical foot displacement together with ROM of the foot in front crawl and back crawl to explore the difference in swimming performance between the two strokes. It is also necessary to investigate the vertical displacement of the other parts of the body namely - knee, mid-hip, mid-shoulder, and COM, since the vertical displacement of the foot is not only defined by the motion of the knee joint, but also by the vertical displacement of these parts of the body. The vertical displacement of the knee is especially important since it defines the position of the thigh, which potentially increases the cross sectional area created by the lower limbs, and thus, resistive force. To consider the effect of leg kicking on difference in front and back crawl performances, it is also important to investigate the difference in 3D speed of the foot between the strokes because the faster the foot speed, the greater kinetic energy the swimmer imparts to the water at a given ROM of the foot. Lerda & Cardelli (2003) reported swimmers conducted 6.11 kicks in one stroke cycle (including both left and right kick) at the speed of $1.44 \text{ m} \cdot \text{s}^{-1}$ with SF of $37.17 \text{ cycles} \cdot \text{min}^{-1}$ in back crawl, which indicates kick frequency (KF) of 1.89 Hz. On the other hand, Zamparo, Pendergast, et

al. (2005) reported KF of 1.17, 1.25, 1.43, 1.57, and 1.63 Hz at swimming speed of 1.0, 1.1, 1.2, 1.3 and 1.4 $\text{m} \cdot \text{s}^{-1}$ respectively in front crawl. A simulated KF at 1.44 $\text{m} \cdot \text{s}^{-1}$ in the study of Zamparo, Pendergast, et al. (2005) using a linear regression equation ($KF = 1.24 \cdot \text{swimming speed} - 0.078$) is 1.71 Hz, which is lower than kick frequency in back crawl at the same speed, which indicates the possibility of faster 3D foot speed in back crawl than in front crawl assuming that ROM of the foot is the same.

ROM, the vertical displacement, and ROM of the foot potentially affects the resistive force and energy expenditure of the swimmer, and thus, it is possible that the foot kinematic variables are responsible for the difference in swimming performance between front crawl and back crawl. However, with an exception of the study by Cappaert (1999) in which similar ROM of the foot between front crawl and back crawl are reported, no attempts have been made to investigate the differences in foot kinematics between front crawl and back crawl. Considering that these kinematic variables are affected by swimmer's anthropometric characteristics (such as the length of upper and lower legs), it is necessary to investigate the differences in the kinematic variables between the strokes performed by the same group of swimmers.

2.8. Summary of Literature Review

To investigate the differences between front crawl and back crawl, it is important to consider the differences in the swimming speed (V), stroke frequency (SF), stroke length (SL), stroke index (SI), the energy expenditure (\dot{E}), swimming efficiency (η), resistive force, and propulsive force between the strokes.

It has been reported that swimmers had faster V , higher SF , shorter SL , and higher SI in front crawl than in back crawl. However, although all these variables are affected by swimmers' anthropometric characteristics (and thus, to compare different groups of swimmers for each stroke might produce errors), no attempts have been made to compare these variables between the two strokes using the same group of swimmers. To investigate the differences in these variables, it is important to conduct 3D motion analysis to investigate detailed COM and other kinematics which affect these variables (such as duration of each phase, the range of motion, and the effect of the torque applied on the arm) with appropriate definition of the stroke phases.

To investigate the physiological difference between front crawl and back crawl, it is necessary to compare the energy cost (C) of swimmers during the two strokes. There have been some studies in which C of front crawl and back crawl were compared. Although higher C during back crawl relative to front crawl has been reported in the literature, the accuracy of the results of those studies are questionable because of methodological issues. Although the anaerobic \dot{E} has been assessed in both front crawl and back crawl in some studies, the accuracy of assessing \dot{E} at anaerobic exercise intensity is still in controversial. It is also necessary to assess the \dot{E} during swimming using a portable gas analyser and a light respiratory valve and snorkel to investigate the energy cost of the strokes together with 3D motion analysis.

To make the link between physiological and biomechanical differences between front crawl and back crawl, it is important to compare swimming efficiency (η) of the two strokes. There are two η which have been used in swimming researches – namely the drag efficiency (η_D) and Froude efficiency (η_F : which is regarded as the propelling efficiency in some studies). Although to measure η_D has an advantage that it can reflect the balance of the physiological work (input) and the biomechanical work (output), to measure the active drag, which is the variable reflects the biomechanical work, is quite difficult. η_F has been calculated using

either active drag based estimation and kinematics (and a mathematical model) based estimation. As mentioned above, to measure the active drag during swimming is still difficult. Furthermore, the method used for calculating η_F in previous studies is based on active drag estimation using the MAD-system, which is not applicable for back crawl. Thus, to compare the η between front crawl and back crawl, the most appropriate way is to calculate η_F using kinematic variables – namely the COM speed and the 3D relative hand speed. Although this method still has limitations, it is currently the only method of comparing the swimming efficiency between front crawl and back crawl based on the same efficiency criteria. This calculation also has a benefit that the contribution of each stroke phases on η_F can also be explored. η_F is a variable which only reflects the efficiency of the arm stroke, and thus, it is important to assess foot kinematics (such as the range of motion, and foot speed) because kicking motion affects the internal work of the swimmer, even though it has been reported that the contribution of the kicking on the propulsion is small. Similarly, it is also difficult to measure the propulsive force applied on the water by the swimmer. However, it is possible to consider the difference in the net force (resistive force and propulsive force) between front crawl and back crawl using the intra-cycle velocity variation (*IVV*) of the swimmer. Several researchers have investigated the difference in the *IVV* between front crawl and back crawl. However, these studies had methodological limitations such as the use of a single joint (e.g. hip) or the calculation based on 2D motion analysis. Thus, it is necessary to compare *IVV* of COM between front crawl and back crawl using 3D motion analysis. To investigate other kinematic variables such as yaw angle fluctuation, lateral distance between the hand and COM, and vertical displacement of COM, shoulder, hip, knee, angle are also useful to discuss the potential differences in the resistive force between front crawl and back crawl.

It has been suggested that the body roll angle of the swimmer also affects the resistive and propulsive forces during the stroke cycle, although there have not been many studies to

establish a direct relationships between the roll angle and propulsive and resistive forces. Although characteristics of the body roll in front crawl have been investigated by many researchers, there have been few studies of back crawl body roll angle. Considering that the possible relationship between the roll angle and the forces, and that the body roll angle is one of the kinematic factors which are in common between front crawl and back crawl, it is necessary to investigate the difference in the body roll angle between the two strokes.

The coordination of right and left arms is also a variable to investigate since it potentially affects *SF* of the swimmer in front crawl and back crawl. Although the index of coordination (*IdC*) has been commonly used to assess the coordination in front crawl and back crawl, the methods used in earlier research possibly varied among the studies and the methods used to calculate *IdC* differed for front crawl and back crawl. Thus, it is necessary to establish a different way of assessing coordination for front crawl and back crawl to compare the strokes based on the same definition (e.g. to measure the timing of the entry of an arm in relation to the duration of the other arm).

To explore the difference in *SF* between the strokes, it is also important to investigate the difference in hand path distance during the stroke cycle since it reflects the range of motion of the upper limbs, which is a factor determining *SF* during swimming.

Many studies have been conducted to investigate biomechanical and physiological characteristics in front crawl. However, the number of studies in which the characteristics in back crawl were investigated is limited. Moreover, although several researchers have reported biomechanical and physiological differences between front crawl and back crawl, the accuracy of the results are questionable because of methodological issues. Furthermore, few attempts have been made to compare front crawl and back crawl performed by the same swimmers, which is essential to explore the differences between the strokes since many biomechanical and physiological factors are affected by swimmers' anthropometric/physiological characteristics. Thus, to explore biomechanical and

physiological differences between front crawl and back crawl, it is necessary to compare the two strokes performed by the same swimmers with accurate and reliable methods (such as 3D motion analysis, accurate calculation of COM position, and the use of portable gas analyser and respiratory valve and snorkel).

Chapter Three
Methods

Section 3.1 details the participants in this study. Section 3.2 describes establishment of the testing speeds for Study 1 and Study 2. Section 3.3 describes the method of the first study which was an investigation of the differences in the energy expenditure and 3D kinematics between front crawl and back crawl below the anaerobic threshold. Section 3.4 describes the method of the second study which included 3D motion analysis for front crawl and back crawl at the same speed above the anaerobic threshold. The last section (3.5) describes the methods used in Study 3, which was to explore differences in kinematics between the strokes at the same exercise intensity above the anaerobic threshold, and an investigation of the relationship between isokinetic muscular torque and 3D kinematics parameters in front crawl and back crawl. Section 3.6 explains the statistical analysis used in Study 2 and Study 3.

3.1. Participants

The participants were 10 Portuguese male swimmers. The participants' personal best records for both 100m front crawl and 100m back crawl were equivalent to be ranked in the top 200 Portuguese swimmers in those events. The participants' best records were at least 78% of 100m world record (100m front crawl: 44.94 seconds, 100m back crawl 48.94 seconds: Short course world records, August 2013). Table 3.1 shows age, height, mass, specialist, 100m personal best records in front crawl (FC) and back crawl (BC) of each participant. Height and mass of the participants were measured prior to the first testing session.

Table 3. 1: Information of the participants. 100mFC and 100mBC show their personal best records (both in seconds and the percentile of the records relative to the world records) in 100m front crawl and back crawl respectively.

Participant	Age (years)	Height (cm)	Weight (kg)	Specialist	100mFC [s(%WR)]	100mBC [s(%WR)]
1	18.42	174.30	65.30	Front crawl	55.70 (80.68)	61.80 (79.19)
2	17.50	175.10	75.90	Medley	53.20 (84.47)	61.20 (79.97)
3	17.17	180.00	71.00	Medley Butterfly	54.54 (82.40)	61.70 (79.32)
4	19.58	188.10	81.20	Front crawl	54.50 (82.46)	62.00 (78.94)
5	17.25	184.80	74.80	Front crawl Back crawl	55.01 (81.69)	62.00 (78.94)
6	17.42	179.20	64.80	Back crawl Breast stroke	55.70 (80.68)	58.80 (83.23)
7	16.50	175.40	62.90	Medley	54.00 (83.22)	59.80 (81.84)
8	16.58	175.60	63.80	Back crawl	55.32 (81.24)	59.49 (82.27)
9	18.00	186.10	76.40	Front crawl	51.80 (86.74)	59.32 (82.50)
10	16.25	173.00	64.30	Back crawl	55.30 (81.27)	59.45 (82.35)
Mean	17.47	179.14	69.94	-	54.50 (82.49)	60.56 (80.85)
SD	1.00	5.43	6.54	-	1.23 (1.91)	1.29 (1.72)

3.2. Establishment of the Testing Speed for Study 1 and Study 2

The purpose of Study 1 was to quantify both physiological and biomechanical differences at an aerobic exercise intensity to assess whether front crawl is more economical than back crawl at this intensity. The purpose of Study 2 was to investigate biomechanical differences between front crawl and back crawl at anaerobic exercise intensities to assess whether front crawl is more efficient than back crawl at this intensity, and to assess which kinematic

factors make front crawl to be faster than back crawl. To achieve these purposes, testing speeds for the studies had to be defined carefully.

In Study 1, the difference in the energy expenditure between front crawl and back crawl was assessed at the moderate intensity (aerobic exercise intensity) which is defined as the intensity swimmers can maintain for hours without exhaustion (Zacca & Castro, 2012). At this intensity the energy required for the activity is maintained through aerobic metabolism and is below the threshold at which lactate accumulates due to the shortfall in energy produced by aerobic processes. At intensities above the anaerobic threshold, the additional energy required is supplied by anaerobic metabolism without complete oxidation, thereby, resulting in lactate accumulation. However, measurement of the energy contribution above the anaerobic threshold is controversial. Although a common method for assessing anaerobic energy was based on the assumption that the energy equivalence for blood lactate accumulation is $2.7\text{mlO}_2\cdot\text{mM}^{-1}\cdot\text{kg}^{-1}$ (Di Prampero et al., 1978), Thevelein et al. (1984) suggested that individual differences for the energy equivalence of the lactate production were too large to be ignored. Also, blood lactate could severely underestimate muscle lactate concentrations (Scott & Kemp, 2005). For these reasons, Study 1 was conducted at a moderate intensity, and to define the intensity, the anaerobic threshold (AnT), at which anaerobic energy pathways start to operate, and the velocity of the anaerobic threshold ($vAnT$) were defined.

To conduct the testing at the same selected exercise intensities in Study 2, the testing speed had to be defined based on the same physiological standard. Table 3.2 shows the relationship between race speeds and swimming speed at Onset of Blood Lactate Accumulation ($vOBLA$) which is the speed at which swimmers show blood lactate accumulation of 4mmol (Dekerle, Pelayo, Sydney, & Marais, 1999; Di Prampero, Dekerle, Capelli, & Zamparo, 2008; Wakayoshi et al., 1992, 1993). Table 3.2 shows that all of these studies reported the similar relationships between $vOBLA$ and race speeds, and thus, $vOBLA$ can be a good indicator of

swimming race speeds. Therefore, in this project, $vOBLA$ was determined to decide the testing speed in Study 2.

Table 3. 2: Relationships between OBLA and race speeds of swimmers (%).

Relationship Between OBLA and Race Speeds		Dekerle et al., (1999)	Wakayoshi et al., (1993)	Wakayoshi et al., (1992)	Rodriguez et al., (2003)	Mean
$vOBLA$ (% Race Speed)	50m	76.54				76.54
	100m	81.43			81.87	81.65
	200m	87.90	86.33	86.36		86.86
	400m	93.12	92.05	93.84	94.52	93.38
Race Speed (% $vOBLA$)	50m	130.65				130.65
	100m	122.80			122.14	122.47
	200m	113.77	115.83	115.80		115.13
	400m	107.39	108.64	106.56	105.80	107.10

Both $vAnT$ and $vOBLA$ were determined in accordance with Fernandes, Sousa, Machado, & Vilas-Boas (2011). An incremental swimming test was conducted in a swimming pool (25m×6 lanes). Incremental tests are widely accepted methods to determine $vAnT$ and $vOBLA$ (Fernandes et al., 2010, 2011; Pyne, Lee, & Swanwick, 2001; Toubekis, Tsami, & Tokmakidis, 2006). The testing protocol comprised 7×200m repeat swims until the swimmer could not follow the specified swimming speed with 30 seconds rest between each trial, and with $0.05\text{m}\cdot\text{s}^{-1}$ increment of swimming speed per each trial. The initial speed of the incremental test was set at $0.3\text{m}\cdot\text{s}^{-1}$ less than the mean speed of 400m maximum effort performances of each swimmer for both front crawl and back crawl. The accuracy of this protocol to measure individual $vAnT$ had been established previously by Fernandes et al. (2011), in which a significant correlation between $vAnT$ measured by the incremental test

and v_{AnT} measured by a maximum lactate steady state test was observed ($r=0.84$, $p<0.01$).

The swimming speed of the swimmers was controlled by a visual light pacer (Pacer2, GBK-Electronics, Aveiro, Portugal). Prior to the testing, swimmers were instructed to conduct an individual warm up session which included a familiarisation period for the light pacer.

Visual light pacers had been commonly used as a pace controlling device in many swimming studies (Barbosa, Fernandes, et al., 2006; Barbosa, Lima, et al., 2006; Fernandes, Marinho, et al., 2006; Laffite et al., 2004; Marinho et al., 2006; Reis et al., 2010; Vilas-Boas, Fernandes, Barbosa, & Keskinen, 2007). Since the condition of the incremental test had to be the same as the energy expenditure measurement in Study 1 in which the energy expenditure would be determined by oxygen uptake, swimmers were instructed to wear a snorkel and respiratory valve in the incremental test. Also, swimmers were instructed to do a push-start, and open turn without underwater kicking because the length of the snorkel allowed swimmers to swim only around the surface (Barbosa, Silva, et al., 2010; Bentley et al., 2005). Although each swimmer's motion had to be restricted around the wall because of the snorkel device, Barbosa, Silva, et al (2010) suggested that the use of this snorkel did not change a swimmer's motion in the middle of the pool. It should be noted, however, that Barbosa, Silva, et al (2010) only investigated simple kinematic variables (i.e. SF , SL , SI and IVV), and the change of detailed kinematic variables such as body roll angle or hand and foot kinematics were unknown. Furthermore, Barbosa, Silva, et al. (2010) did not investigate the differences in kinematic variables in back crawl with and without the snorkel device.

Considering that the snorkel device is constantly above the water in back crawl, the effect of wearing the snorkel device on kinematic variables would be rather smaller in back crawl than in front crawl because the snorkel would not create any additional resistive force.

However, the extra mass on the head of the swimmer might affect the location of COM of the swimmer throughout the stroke in both front crawl and back crawl. In fact, in the study of Barbosa, Silva, et al. (2010) showed slight difference in COM speed pattern during the stroke cycle between front crawl trials with and without the snorkel, even though there were

no differences in mean COM speed and *IVV*. This possible effect of wearing snorkel on kinematic variables in front crawl and back crawl was a limitation of this study.

To avoid the possible error due to swimmer's unfamiliarity of the snorkel device, the participants were required to use snorkels in both front crawl and back crawl in their daily training for a week prior to the testing sessions. On the day of the testing sessions, the participants also had 15 minutes of familiarisation period for the snorkel device used in the testing protocol after the individual warming up.

To determine the *vAnT* and *vOBLA*, a blood sample was taken from a fingertip of the swimmer before the protocol, and after each stage (within 30 seconds) of the protocol to measure the blood lactate value using Lactate Pro (Arkay, Inc, Kyoto, Japan). Accuracy and reliability of the device have been verified by several authors (Baldari et al., 2009; Pyne, Boston, Martin, & Logan, 2000; Tanner, Fuller, & Ross, 2010). The blood lactate value was plotted on the graph as a function of the velocity. The anaerobic threshold was defined as the intersection of two regression lines (one regression line and one exponential line) which were fitted to the lactate curve (Fernandes et al., 2011; Svedahl & MacIntosh, 2003; Tokmakidis & Léger, 1992) and *vOBLA* was also defined based on the graph (Figure 3.1). It should be noted that it has been reported that the blood lactate concentration becomes highest several minutes after the swimming, and not immediately after (Stirn, Jarm, Kapus, & Strojnik, 2011), and thus, the lactate value measured in this protocol might have underestimated the blood lactate value. Nevertheless, considering the accurate *vAnT* assessed by Fernandes et al. (2011) using this protocol, and that the calculation of *vAnT* is based on the shape of regression lines (linear and exponential) rather than the lactate value itself, the possible underestimation of the blood lactate value should not affect the calculation of *vAnT*. On the other hand, it is possible that this possible error causes slight overestimation of *vOBLA*. However, the main purpose of using *vOBLA* as a base of the testing speeds in Study 2 and Study 3 is to establish the testing speeds of both front crawl and back crawl based on

the same physiological intensity. Therefore, the possibility of overestimation of $vOBLA$ would not produce issues to achieve the aim of this study as long as the speeds were established based on the same physiological criteria.

The incremental protocol was conducted for both front crawl and back crawl with at least 24 hours interval between each stroke to avoid the effect of fatigue. Ivy (1991) suggested that 24 hours is sufficient to restore muscle glycogen recovery. King & Duffield (2009) also observed that 24 hours recovery between exercise was sufficient to allow performance to be maintained.

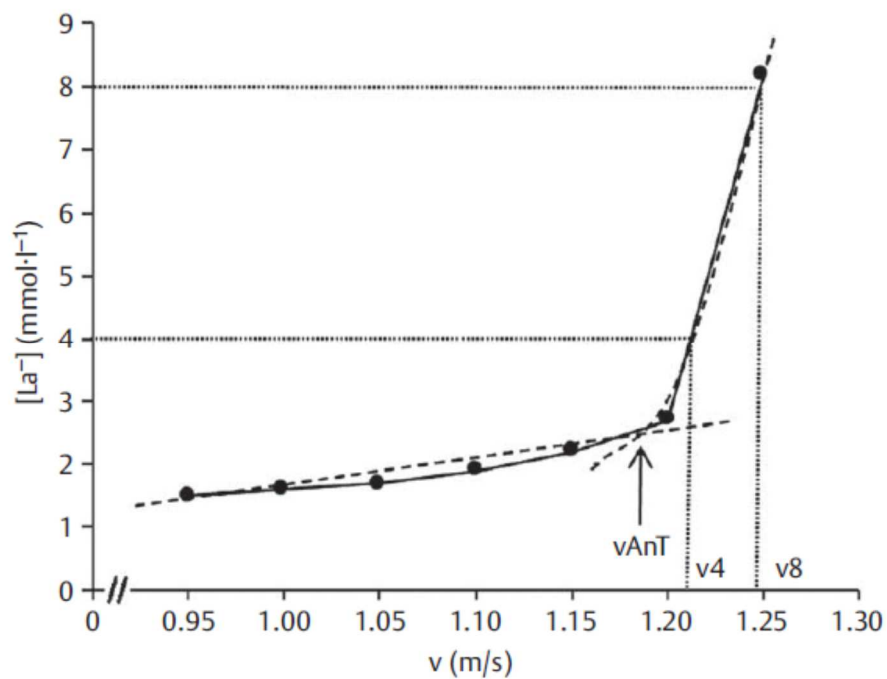


Figure 3. 1: Individual v_{AnT} and $vOBLA$ (v_4) assessment (Fernandes et al., 2011).

3.3. Study 1

In this section, the methods used in study 1, which was to investigate the differences in energy cost and 3D kinematics between front crawl and back crawl under the anaerobic threshold, is explained.

3.3.1. Testing Protocol

3.3.1.1. Calibration of the Testing Lane

Figure 3.2 shows the experimental set-up in this study. The testing was conducted in the centre of the pool to optimise the distance for all cameras (total of 6 cameras: 2 above the water, 4 under water). Prior to the testing, the testing lane was calibrated by a calibration frame with dimensions of 6m length, 2.5m height, and 2m width (total volume of 30m³) with 64 control points (32 underwater, and 32 above the water control points). This calibration frame was designed for 3-D Direct Linear Transformation (DLT) method in the water. The control points of the calibration frame were clearly visible from all cameras. De Jesus, De Jesus, Figueiredo, et al. (2015) investigated the reconstruction error of the calibration frame with manual digitising. In their study, the digitising error of 236 control point were categorised as small error points, medium error points, and large error points using a computer programme. The large error points were treated with manual homography technique for error reduction, and the 3D coordinate was created using over 1 million random sets of the control points. The authors also manually digitised validation points (points which were not used as control points) and investigated the error of the location of the validation points in the coordinate compared with the actual location. As a results, it was concluded that the mean reconstruction error, based on the validation points error

calculation, was less than 8mm (De Jesus, De Jesus, Figueiredo, et al., 2015). The error of less than 8mm represents less than 0.1%, 0.3%, and 0.4% of the calibrated volume for the x, y, and z direction respectively, which are similar or smaller than previous studies (0.4%, 0.5%, and 0.3% for x, y, and z direction: Coleman and Rankin; 2005, 0.1%, 0.2%, and 0.5% for x, y, and z direction: Psycharakis, Sanders, and Mill, 2005). In this study, control points were chosen based on the reported digitising error in the study of De Jesus, De Jesus, Figueiredo, et al. (2015), i.e. only the points which had small digitising error were selected as control points for 3D coordinate production in this study to minimise the reconstruction error.

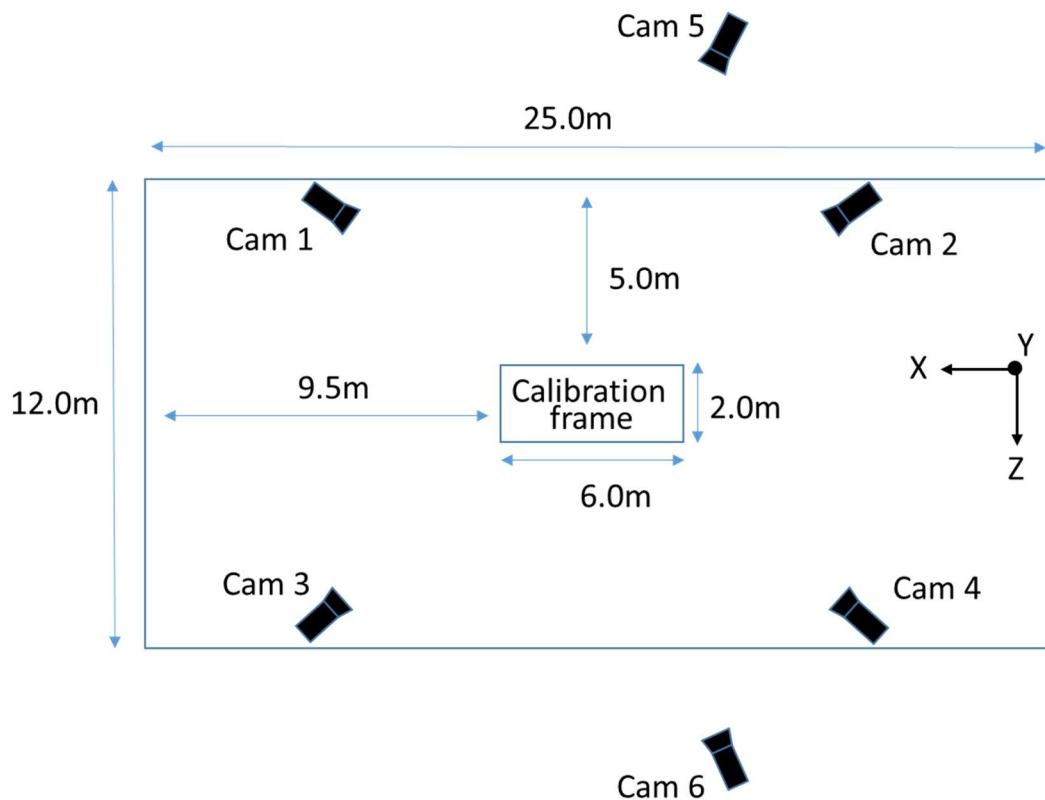


Figure 3. 2: Experimental set-up for three-dimensional analysis. Cam 1-4: underwater cameras. Cam 5 & 6: above the water cameras.

3.3.1.2. Participants' Preparation and Anthropometric Data Collection

Prior to the testing, participants were marked on anatomical landmarks: the vertex of the head, acromioclavicular joint, greater tubercle of the humerus (shoulder), olecranon process of ulna (elbow), wrist axis, 3rd distal phalanx (finger), greater trochanter (hip), patella axis (knee), lateral malleolus (ankle), 5th metatarsophalangeal joint, and 1st interphalangeal joint (toe). Black oil and wax based cream (Grimas Crème Make Up) was used for the landmarks. For marking the vertex of the head, swimmers were instructed to wear a white silicon cap and a black cream mark was applied on it at the point corresponding to the highest point of the head when the swimmer stood upright. The other markers were painted directly on the skin. Swimmers were required to wear brief swimming trunks so that the hip joint could be clearly identified with a skin marker over the greater trochanter. Additional marks were added to 2nd cervical vertebra, 7th cervical vertebra, and the horizontal plane of the xiphoid process for subsequent calculation of body segment parameter data. For these markers, black tape which is easy to remove was used because these markers would not be required for digitising of the swimming trials.

To obtain personalised body segment parameter (BSP) data of the participants, each participant was captured by digital cameras from front and side view simultaneously to apply the elliptical zone method (Jensen, 1978). In accordance with Deffeyes & Sanders (2005), the cameras were set at 6 metres away from the participants, and image size was maximized in the field of view by zooming. In addition to photographs of the swimmers, photographs of calibration scales were taken in the planes corresponding to the swimmer's frontal and sagittal planes, and to make sure the scale was along with the horizontal and vertical lines, a spirit level was put on the scale (Figure 3.3). Participants were required to stand on an inclined board so that the BSP of the feet could be determined. Participants stood in the anatomical position which is the position with the fingers and thumb adducted with the palms facing forward, elbow extended and shoulders abducted approximately 30 degrees

(Figure 3.4). Participants performed their individual warm-ups after being taken the photographs for BSP data.

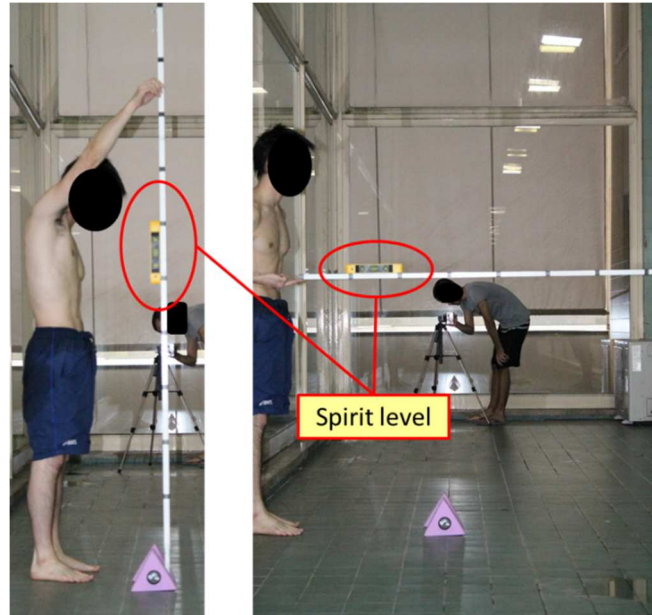


Figure 3. 3: Calibration process for obtaining BSP data.



Figure 3. 4: Anatomical position of a swimmer from frontal and sagittal view.

3.3.1.3. Testing Session

After the warm-up, swimmers performed a 300m test at the intensity of 95% of anaerobic threshold speed (v_{AnT}) because 100 % of v_{AnT} sometimes shows a slight increase in the blood lactate (Fernandes, 2011; Figure.3.5).

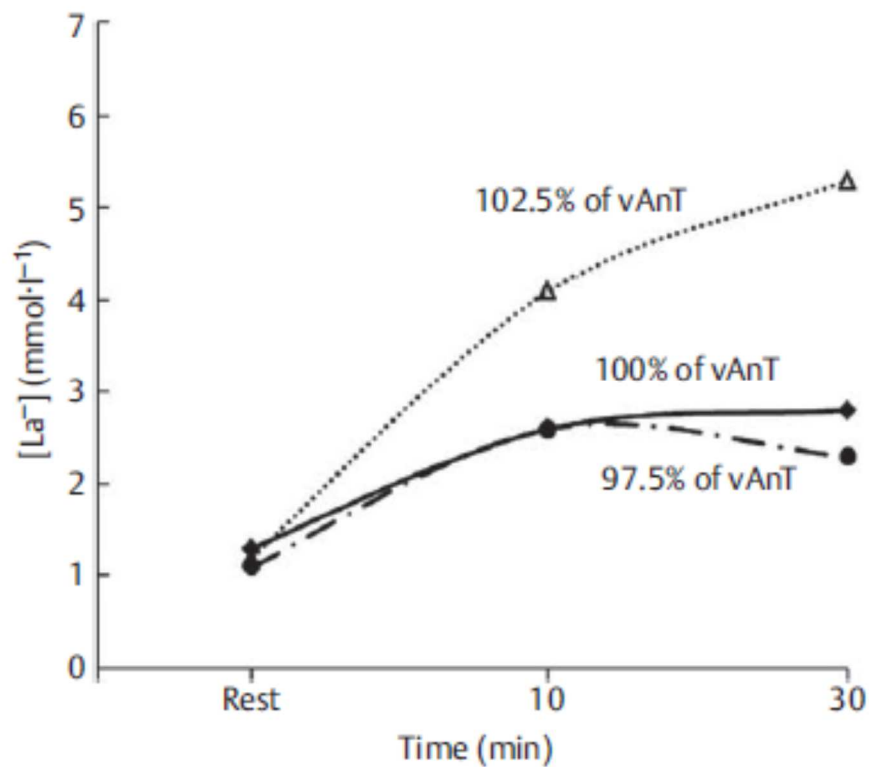


Figure 3. 5: Blood lactate concentration during the maximal lactate steady state test (Fernandes, 2011).

Although 300m front crawl and back crawl are not official race events in competitions, it was necessary to conduct testing at 300m because at least two to three minutes are required to ensure oxygen uptake is steady state (Gaesser & Poole, 1996). The swimming speed of the

swimmers was controlled by a visual light pacer (Pacer2, GBK-Electronics, Aveiro, Portugal). The visual light pacer was a 25m long cable device equipped with 26 LED lights for each meter from 0m to 25m points. The LED lights flashed consecutively to instruct the swimmer the pace the swimmer has to follow according to pre-programmed speed. The pacer was positioned on the bottom of the pool for front crawl trials, and located approximately 2m above the pool with a stainless wire for back crawl trials. The 300m test was repeated twice with at least 24 hours rest between each test. These tests were front crawl test at 95% v_{AnT} of back crawl and back crawl test at 95% v_{AnT} of back crawl respectively. Since energy expenditure is affected by the swimmer's speed (Di Prampero, 1986; Zamparo et al., 2000), it was necessary to compare the energy expenditure between front crawl and back crawl at the same speed to assess the difference. The order of the testing sessions was randomised and the time of 300m front crawl and back crawl were manually measured by a stopwatch (SVAS003, SEIKO, Tokyo, Japan).

3.3.2. Data Collection

Expired gas of swimmers during the swimming trial was collected by AquaTrainer® Snorkel which was connected to a telemetric gas exchange system (K4b², Cosmed, Rome, Italy). Parr et al. (2001) compared \dot{V}_{O_2} value of male participants during cycle ergometer exercise using the Douglas bag and K4b² system, and concluded that there was no difference between the Douglas bag measurement and K4b² measurement, and thus K4b² is an accurate apparatus to measure \dot{V}_{O_2} during the exercise. Baldari et al. (2013) compared \dot{V}_{O_2} of swimmers with AquaTrainer® Snorkel and a respiratory mask, and concluded that AquaTrainer® Snorkel can measure accurate \dot{V}_{O_2} values since \dot{V}_{O_2} values measured by the snorkel and the mask were highly correlated ($R^2=0.99$).

Swimmers' trials were captured by 6 synchronised high definition cameras (four underwater, and two above the water, Sony, HDR-CX160E, Tokyo, Japan, sampling rate: 50 fps, shutter speed: 1/120 seconds, movie resolution: 1920 × 1080/50p) with waterproof camera cases for the underwater cameras (Sony, SPK-CXB, Tokyo, Japan). The six camera images were synchronised using a LED system which was visible from all the six cameras. To maximise accuracy of the DLT calculations, the four underwater cameras and two above water cameras were fixed at different heights and angles to the swimmer's line of motion to avoid the camera axes being in the same plane (Psycharakis, Sanders, and Mill, 2005). The angle between the optical axes of the two above water cameras was approximately 100 degrees, while those of the four underwater cameras were between 75 and 110 degrees in accordance with Figueiredo et al. (2011). Swimmers were instructed to swim directly above the lane-line through the centre of the calibrated space.

3.3.3. Data Processing and Analysis

3.3.3.1. Expired Gas Data

During the testing, swimmer's expired gas was analysed immediately in the gas analyser, and the analysed data (\dot{V}_{O_2} data: ml·min⁻¹) were transferred into the computer in which k4b² software (Cosmed, Rome, Italy) was installed.

After the testing, participants' expired gas was averaged every 5 seconds over each testing stage in accordance with the method previously applied (Sousa et al., 2010; Figueiredo et al., 2011) using the software. The averaged \dot{V}_{O_2} data were then input to an Excel sheet in which the data were normalised by dividing by each swimmer's body mass to express \dot{V}_{O_2} as a unit of ml·kg⁻¹·min⁻¹ in accordance with previous studies (Barbosa et al., 2006; Reis et al., 2010).

The mean $\dot{V}O_2$ value that was achieved at steady state was assumed to be the energy expenditure of each swimmer at the testing speeds.

3.3.3.2. BSP Data

To obtain anthropometric data, photographs of both calibration frames and swimmers in the anatomical position were transferred into a computer. Anthropometric data were then obtained by digitising the landmarks and outlines of the body segments using a MATLAB programme (E-Zone) produced by Deffeyes and Sanders (2005). The E-zone programme calculated segment mass and the location of the segment centre of mass relative to the segment endpoints based on the elliptical zone method.

3.3.3.3. Video Data

The calibration video files and the testing video files of the testing session were transferred into a computer. Since the original video files were AVCHD file, the video files were converted into AVI files using Adobe Premiere Pro (version CC 7.2, Adobe Systems Inc, San Jose, California).

All six camera views were checked to ensure that the swimmer's whole body was in the calibrated space during the selected cycle. The converted video files were then trimmed in Ariel Performance Analysis System (APAS) software (Ariel Dynamics, Inc, CA), and the same software was used to digitise and calculate 3D coordinates. To obtain one complete stroke cycle, the start and the end points of the stroke cycle were defined as the video frame

at which the hand of the swimmer entered the water, and the video frame of the next entry of the same hand into the water. A stroke cycle from the last 25m of the 300m test was chosen for the analysis because the calculation of the energy expenditure was based on the late stage of the testing (approximately the last 45 seconds of the testing). Five extra points before and after the stroke cycle were included in the trimmed video files to minimise errors at the end of the data sets associated with filtering and derivation of velocity and acceleration data. The digitising process was conducted at a frequency of 25-Hz. To ensure the digitising reliability at 25-Hz, a total of ten trials were digitised and the mean and standard deviation of all the variables used in this study were computed. To investigate the accuracy of the 25-Hz digitising, ten random trials were digitised in both 25-Hz and 50-Hz, which is commonly used digitising frequency in swimming studies (Figueiredo et al., 2009; Lauder and Newell, 2009; Psycharakis et al., 2010; Sanders and Psycharakis, 2009), and all kinematics variables used in this study were compared between the trials digitised at each frequency.

Separate 3D coordinates files obtained from the above and the under-water camera views were imported to an Excel file. In the Excel file, those two files were combined, then exported as a single text type file.

The 3D coordinate data and BSP data obtained from the E-Zone analysis were input to a bespoke MATLAB programme. The MATLAB software used in this study was version R2014a (Math Works, Inc., Natick, Massachusetts, US).

The data were smoothed with a 2nd order Butterworth dual pass recursive filter at 4-Hz. This frequency was selected based on experience of frequency content of the data obtained in similar studies that have used the same data collection methods (Sanders and Psycharakis, 2009). This was also supported by Yanai (2003, 2004) who reported that the cut-off frequencies of 2-4 Hz are enough to ensure 95% of the power of original signal retaining in the filtered signal in swimming. To compare kinematic values of different trials which had different cycle times, the output data were expressed in both real time and as percentiles, at

which 0% was the beginning of the stroke cycle, and 100% was the end of the stroke cycle. This was achieved by a Fourier transform with 101 equispaced points between the beginning and end points of the cycle being generated in the inverse transform.

3.3.4. Variables Calculation

3.3.4.1. Swimming Velocity, Stroke Frequency, Stroke Length, and Stroke Index

The centre of mass (COM) was determined by summing the moments of the segment COM mass about the x, y, and z reference axes. The velocity of COM was obtained by differentiate the COM displacement values by the time to compute the mean, maximum, minimum velocity of COM during the stroke cycle. Intra-cycle velocity variation (*IVV*) of the swimmer was computed by the difference between the maximum instant speed during the stroke cycle (IV_{max}) and the minimum instant speed during the stroke cycle (IV_{min}). COM acceleration was also obtained by differentiating the COM displacement data using the second central difference formula for later calculation of COM net impulse (see Section 3.3.4.5).

Stroke frequency (*SF*) was obtained as the inverse of the time that the swimmer takes to complete one stroke cycle which was calculated from the number of the samples for one stroke cycle. Stroke length (*SL*) was measured from the horizontal displacement of the COM during the stroke cycle (McCabe et al., 2011; McCabe and Sanders, 2012). Stroke index (*SI*) was obtained by multiplying *SL* and V_{mean} .

3.3.4.2. Stroke Phases

A stroke cycle was divided into five phases based on previous research: The entry phase, pull phase, push phase, release phase, and above-water (A-water) phase. The entry phase commenced at the instant the wrist enters the water surface and concluded at the instant of first backward movement relative to the external reference frame. The pull phase was defined as from the instant of the end of the entry phase to the instant that the x coordinate of the wrist is the closest to that of the x coordinate of shoulder in the water (i.e. wrist and shoulder are vertically aligned). The push phase was from the end of the pull phase to the instant at which the wrist shows the first positive velocity in swimming direction (x-direction) relative to the external reference frame after the negative wrist movement in swimming direction. The release phase was defined as from the end of the push phase to the instant at which the wrist exits from the water. The A-water phase was defined as from the end of the release phase to the instant of the next entry of the wrist. The duration of each phase was determined from the times of the events on the normalised time record (101 samples per stroke cycle) which yielded greater accuracy in detecting the duration of each phase by providing better temporal resolution than using video frames

The duration of the propulsive phase was calculated by summing the duration of the pull and push phases, and the duration of the non-propulsive phase in the water was calculated by summing the duration of the entry and release phases.

The mean values of left and right phase duration were assumed to represent the duration of each phase of the swimmer in each stroke.

3.3.4.3. Mean Vertical Displacements of Shoulder, Hip, Knee and Foot (Ankle) during the Stroke Cycle

In this study, the mean vertical displacement of the shoulder, hip, knee and foot (ankle) during the stroke cycle were obtained. The vertical displacement of shoulder and hip were determined as the mean vertical displacements of mid-points of the left and right of shoulder and hip during the stroke cycle respectively. The mean vertical displacements of knee and foot were defined as the mean values of the mean left and right vertical displacements of knee and ankle during the stroke cycle respectively.

3.3.4.4. Hand and Foot Kinematics

To calculate hand and foot kinematics, it was assumed that wrist and ankle represented the motion of the hand and foot because it was sometimes difficult to detect the point of finger and toe, especially after the hand entry and the start of the down-beat kick because of the vortex and bubbles. It should be noted that the use of wrist and ankle instead of the midpoint of the hand (i.e. the midpoint of wrist-fingertip vector) might have underestimated the range of motion of the hand and hand speed since the motion of the hand and foot was ignored. Thus, although the use of the wrist and foot had the advantage of minimise the error due to digitising difficulties of the fingertip and the toe, it also had the disadvantage of underestimating some kinematic variables.

3.3.4.4.1. Relative Hand and Foot Path Distance

The relative hand and foot path distance (D_{hand} and D_{foot}) were calculated by summing the distance between wrist/ankle displacements relative to COM between successive samples over the period of interest e.g. underwater phases (Equation 3.1).

$$D_{hand,foot} = \sum_{k=1}^{n-1} \sqrt{(dx_{k+1} - dx_k)^2 + (dy_{k+1} - dy_k)^2 + (dz_{k+1} - dz_k)^2}$$

(Equation 3. 1)

Where n is the last number of the sample in the stroke cycle in the digitising file, dx , dy , and dz are x-displacement (swimming direction), y-displacement (vertical direction), and z-displacement (lateral direction) of the wrist and ankle relative to COM respectively.

3.3.4.4.2. Froude Efficiency and 3D Hand Speed Relative to COM

Froude efficiency (η_F) was calculated by the equation below

$$\eta_F = v_{mean} \cdot 3Du^{-1} \quad (\text{Equation 3. 2})$$

Where V_{mean} is the mean velocity of COM, and $3Du$ is the mean 3D hand speed relative to the COM during the stroke cycle. $3Du$ was calculated by Equation 3.3.

$$3Du = \left(\sum_{k=1}^{n-1} \frac{\sqrt{(dx_{k+1} - dx_k)^2 + (dy_{k+1} - dy_k)^2 + (dz_{k+1} - dz_k)^2}}{time} \right) \cdot (n - 1)^{-1} \quad (\text{Equation 3. 3})$$

where n is the last number of the sample in the stroke cycle, dx , dy , and dz are x-displacement, y-displacement, and z-displacement of the wrist relative to COM respectively, and $time$ is the duration between each sample.

3.3.4.4.3. 3D Foot Speed Relative to COM

3D Foot speed was calculated by Equation 3.4.

$$3Du_{foot} = \left(\sum_{k=1}^{n-1} \frac{\sqrt{(dx_{k+1}-dx_k)^2 + (dy_{k+1}-dy_k)^2 + (dz_{k+1}-dz_k)^2}}{time} \right) \cdot (n-1)^{-1} \quad (\text{Equation 3. 4})$$

where n is the last number of the sample in the stroke cycle, dx , dy , and dz are x-displacement, y-displacement, and z-displacement of the ankle relative to COM respectively, and $time$ is the duration between each sample.

3.3.4.4.4. Range of Motion of the Foot

Range of motion (ROM) of the foot in vertical and lateral direction was assessed by the difference between the maximum and minimum displacements of the ankle in both the vertical and lateral directions respectively. The calculation was conducted in both left and right ankles, and the mean values of the left and right ROM values in both vertical and lateral direction are reported in this study.

3.3.4.4.5. Hand Speed and Acceleration during the Propulsive Phase

Hand speed was calculated by differentiating the wrist displacement (x, y, z displacements to obtain x, y, z hand speeds respectively) relative to the external reference frame with respect to time, and hand acceleration was calculated by differentiating the hand speed with respect to time. The hand speed and acceleration toward the swimming direction was calculated only during the propulsive phases (pull and push phases), and the hand speeds in vertical (y) and lateral (z) directions were calculated during the whole underwater phases.

3.3.4.5. Body (Shoulder and Hip) Roll Angle

Shoulder and hip roll angles (S_{roll} and H_{roll}) were determined as the angles between the unit vector of the line joining the shoulder and hip joints projected onto the y-z plane, and the horizontal (Equation 3.5 and 3.6), in accordance with previous studies (Psycharakis and McCabe, 2011; McCabe et al., 2011; McCabe and Sanders, 2012).

$$S_{roll} = \text{atan}(S_z \cdot S_y^{-1}) \quad (\text{Equation 3. 5})$$

$$H_{roll} = \text{atan}(H_z \cdot H_y^{-1}) \quad (\text{Equation 3. 6})$$

Where S_z and H_z are z (lateral) components of the shoulder and hip unit vectors, and S_y and H_y are y (vertical) components of the shoulder and hip unit vectors. The maximum roll angle in both left and right hand sides were computed, and the mean value of the left and right roll angles are reported in this study.

3.3.4.6. COM Net Impulse

The COM net impulse during the propulsive phase was calculated as time-integrated COM net force, which is the product of COM acceleration and the mass of the swimmer during the pull and push phases.

3.3.4.7. Yaw Angle Fluctuation

Swimmer's yaw angle was defined as the angle between the trunk (middle hip-middle shoulder vector) and the longitudinal axis of the external reference frame (x-axis). The yaw angle fluctuation was defined as the difference between the maximum yaw angle and the minimum yaw angle.

3.3.4.8. The Distance between the Hand and COM in Lateral-direction

The difference between the hand and COM in lateral-direction ($Z\text{-Distance}_{\text{Hand-COM}}$) was computed by subtracting the lateral displacement (z-displacement) value of COM from the lateral displacement value of the wrist. The wrist was assumed to represent the hand displacement to avoid the effect of possible digitising error due to turbulence and bubbles around the hand and fingers. The maximum $Z\text{-Distance}_{\text{Hand-COM}}$ during the stroke cycle and the time corresponding to $Z\text{-Distance}_{\text{Hand-COM}}$ are reported in this study.

3.3.5. Statistical Analysis

To assess the significance of the difference of the energy cost and all the kinematics values between front crawl and back crawl at the same speed, a paired t-test was used. Statistical significance was set at $p < 0.05$. Prior to the t-test, the normality of all data in front crawl and back crawl was checked and confirmed using Kolmogorov–Smirnov test. To provide a further indication for the outcome difference, effect size (Cohen’s d) was calculated. According to Cohen (1988), d values of 0.20, 0.50, and 0.80 represent small, medium, and large effects respectively. The paired t-test was conducted using IBM SPSS Statistics 19 (IBM Corporation, Somers, NY, USA), and the calculation of the effect size was conducted based on the following equation in accordance with Pace (2012).

$$d = \frac{|M|}{SD} \quad (\text{Equation 3. 7})$$

Where M is the mean difference, and SD is the standard deviation of the mean differences.

3.4. Study 2

In this section, the methodology used in the study 2 is explained. Study 2 was conducted to assess the differences in 3D kinematics between front crawl and back crawl at the same selected speeds.

3.4.1. The Testing Protocol for 3D Kinematic Data Collection

Prior to the video recording, the same procedures for participant preparation and calibration as Study 1 were conducted (see 3.3.1.1 and 3.3.1.2). After taking the photographs required for estimation of BSP data by the E-Zone programme, participants performed an individual warm-up. Participants were instructed to include sprint front crawl or back crawl in the warm-up depending on the stroke style in the following testing. Then swimmers were required to complete four times 50m swims at the speed of 130% *vOBLA*, 122% *vOBLA*, 115% *vOBLA*, 107% *vOBLA* with four minutes rest, since these speeds represent swimmer's 50m, 100m, 200m, and 400m performance (see Section 3.2). Both front crawl and back crawl trials were conducted using testing speeds based on back crawl *vOBLA*. Since the *vOBLA* in this project was determined under the condition of swimmers wearing the valve and snorkel, *vOBLA* without snorkel and valve condition was assumed to be 5% higher than the *vOBLA* obtained in the incremental protocol. This assumption was based on a finding in a previous study in which 5% longer swimming time of the swimmer with the valve and snorkel than without the valve and snorkel condition (Barbosa, Silva, et al., 2010). The speed of the swimming was controlled by Pacer2 visual light pacer (GBK-Electronics, Aveiro, Portugal). The four times 50m trial for front crawl and back crawl were conducted on different days. 130% *vOBLA* trials were supposed to be equal to 50m sprint (i.e. maximum effort trials), and thus, the participants were required to swim with their maximum effort in

130% *vOBLA* back crawl trials regardless the instructed speed. For all swimmers, the date of back crawl trials were prior to the date of front crawl trials so that the speed of the fastest trial for front crawl would be able to be adjusted in case swimmers exceeded (or could not follow) the instructed speed in the fastest trials in back crawl. All trials were manually timed using a stopwatch (SVAS003, SEIKO, Tokyo, Japan) to ensure the swimmers achieved the instructed swimming speeds (instructed 50m times). The order of each testing speed was fully randomised to avoid any effects of the fatigue during the trial. All trials were initiated from a push start to avoid any influence of the dive on the stroke kinematics (Cardelli, Lerda, & Chollet, 2000; Psycharakis et al., 2010; Toubekis, Douda, & Tokmakidis, 2004). Every trial started from the side of the pool and swimmers were not allowed to perform underwater kicking after the start and turns to ensure capturing one whole stroke cycle in the calibrated area, and to avoid the effect of underwater kicking on free swimming performance. When swimmers deviated from the calibrated space or desired swimming direction, the trial was repeated. During the front crawl trials, swimmers were not permitted to breathe while swimming through the calibrated area to avoid possible effects of the breathing on kinematics in swimming.

3.4.2. Data Collection

To obtain BSP data of the participants and the video data during the testing for the motion analysis, the same strategy as study 1 was used (see 3.3.1 and 3.3.2).

3.4.3. Data Processing and Analysis

3.4.3.1. BSP Data and 3D Coordinates of the Swimming Trials

Photographs from E-zone testing, calibration video files, and the video files from the swimming testing were all treated using the same method of Study 1 to get anthropometric data of the participants and 3D coordinates for all swimming trials (see 3.3.3.2 and 3.3.3.3).

3.4.3.2. Calculation of Variables

COM displacement and speed, IVV , SF , SL , SI , duration of each phase, body roll angles, hand speed and acceleration, 3D hand path distance relative to COM, 3D hand speed relative to COM, displacement of the foot in vertical direction, and η_F , were calculated by the same process as Study 1 (see 3.3.4). In this section, the kinematic variables calculated only in Study 2 are described.

3.4.3.2.1. Mathematical Contribution of Each Phase to Differences in the 3D Hand Speed

To investigate the factors which caused differences in 3D hand speed relative to COM ($3Du$), which was used for obtaining η_F , the following mathematical method was used.

Mathematically, $3Du$ during the stroke cycle ($3Du_{SC}$) can be calculated using the hand path distance relative to the centre of mass during each and the duration of the stroke cycle (Equation 3.8).

$$3Du_{SC} = \frac{Hpath_{Entry}}{t_{SC}} + \frac{Hpath_{Pull}}{t_{SC}} + \frac{Hpath_{Push}}{t_{SC}} + \frac{Hpath_{Release}}{t_{SC}} + \frac{Hpath_{AWater}}{t_{SC}} \quad (\text{Equation 3. 8})$$

Where $Hpath_{phase}$ is the hand path distance of each phase (m) and t_{SC} is the total duration of the stroke cycle (seconds). Since the hand path distance is multiplication of the 3D hand speed and the duration, the equation can be transferred into Equation 3.9.

$$3Du_{SC} = \frac{3Du_{Entry} \cdot t_{Entry}}{t_{SC}} + \frac{3Du_{Pull} \cdot t_{Pull}}{t_{SC}} + \frac{3Du_{Push} \cdot t_{Push}}{t_{SC}} + \frac{3Du_{Release} \cdot t_{Release}}{t_{SC}} + \frac{3Du_{AWater} \cdot t_{AWater}}{t_{SC}} \quad (\text{Equation 3. 9})$$

Where $3Du_{phase}$ is the mean 3D hand speed during each phase ($m \cdot s^{-1}$), t_{phase} is the duration of each phase (seconds), and t_{SC} is the duration of the stroke cycle (seconds). Equation 3.10 suggests that the mean 3D hand speed during the stroke cycle is determined by mean 3D hand speed in each phase and the relative duration of the phase (the duration of the phase in relation to stroke cycle duration). In other words, the faster the mean 3D hand speed in a phase, and/or the longer the duration of the phase in relation to the cycle duration, the phase makes the mean 3D hand speed during the stroke cycle faster.

Thus, to investigate which phases are responsible for the difference in the mean 3D hand speed during the stroke cycle, the product of the mean 3D hand speed in each phase and the relative duration of the phase ($\frac{3Du_{phase} \cdot t_{phase}}{t_{SC}}$ in Equation 3.9) during the stroke cycle was

compared between the strokes. The phases which had the same tendency in

$3Du_{phase} \cdot (t_{phase}/t_{SC})$ as the difference in $3Du_{SC}$ was assumed to contribute positively to the difference in $3Du_{SC}$. (e.g. if $3Du_{SC}$ in back crawl is significantly faster than in front crawl,

phases in which $3Du_{phase} \cdot (t_{phase}/t_{SC})$ is significantly larger in back crawl than in front crawl are considered to be responsible for the faster $3Du_{SC}$ in back crawl).

3.5. Study 3

In this section, the methodology used in the study 3 is described. Study 3 was conducted to assess the differences in 3D kinematics between front crawl and back crawl at the same selected exercise intensities. In this study, the relationships between swimming performance and isokinetic torque in the two strokes were also investigated.

3.5.1. Testing Protocol

3.5.1.1. Isokinetic Torque Measurement

3.5.1.1.1. Types of Shoulder Motions for the Measurement

In this study, isokinetic torques during three sets of shoulder motion - namely shoulder flexion/extension, abduction/adduction, and internal/external rotation were investigated. These three shoulder motions have been suggested to be related to swimming motion or swimming record (Miyashita & Kanehisa, 1979; Payton et al., 1997; Pink et al., 1992; Yanai & Hay, 2000). The muscular torque of the lower body was not examined since normally both front crawl and back crawl show almost the same kicking technique (E. Maglischo, 2003; Prins, 2007).

3.5.1.1.2. Dynamometer Setting

An isokinetic dynamometer (Biodex® System 4, Biodex Corporation, Shirley NY.) was used to measure isokinetic torques of the swimmers. Prior to the testing, participant's height and

mass were measured since these variables were required to operate the dynamometer. The isokinetic dynamometer was connected to a computer in which BIODEX 4 pro software 4 (Biodex®, Biodex Corporation, Shirley NY.) was installed. Prior to the testing, participant's mass, height and dominant side were manually input to the software. To measure shoulder isokinetic torques, each participant was instructed to sit on the dynamometer seat with the torso strapped at the shoulders and pelvis to minimize any extraneous movement. The orientation and the tilt angle of the seat and the dynamometer were adjusted to the angles which were suggested in the BIODEX instruction manual. After the angles were set at the proper position, hand grip and extension bar were fitted on the dynamometer. The length of the bar was adjusted so that the participant did not feel any physical discomfort throughout the whole range of motion of the exercise.

3.5.1.1.3. Testing Session

The participant was instructed to conduct a five minute period of dynamometer shoulder exercise as a warm-up and familiarization with the measurement apparatus. The warm up and familiarization procedure was conducted before each shoulder rotation exercise. The participants were instructed to do three repetitions of 60 deg·s⁻¹ and twenty repetitions of 180 deg·s⁻¹. The number of the repetition was based on a pilot work (unpublished) in which all participants achieved peak torque in the first 3 repetitions out of 20 repetitions at 60 deg·s⁻¹ trials, whereas some participants achieved their peak torque in the latter half of 20 repetitions at 180 deg·s⁻¹ trials. The number of the repetitions was also in accordance with previous studies (Batalha et al., 2012, 2013). The testing protocol was based on the extant literature in which *SF* in front crawl and back crawl range from approximately 20 cycles·minute⁻¹ to 60 cycles ·minute⁻¹ depending on the swimming speed (Table 3.3 and 3.4). Although the authors

in the tables did not measure the angular velocity of the upper arm, SF ($\text{cycles}\cdot\text{s}^{-1}$) can be converted into mean angular speed of the hand around the shoulder during swimming by multiplying it by 360 because $1 \text{ cycles}\cdot\text{s}^{-1}$ can be assumed to be $360 \text{ deg}\cdot\text{s}^{-1}$ since stroke movement in swimming is a circular movement. According to SF data in the previous studies, the mean angular speed of the hand around the shoulder of the swimmer was approximately $150 - 380 \text{ deg}\cdot\text{s}^{-1}$ in front crawl, and $130 - 300 \text{ deg}\cdot\text{s}^{-1}$ in back crawl (Table 3.5 and 3.6). In this study, however, the testing was not conducted at the angular velocity larger than $180 \text{ deg}\cdot\text{s}^{-1}$, because Mayer et al. (2001) suggested that the torques obtained at speeds greater than $180 \text{ deg}\cdot\text{s}^{-1}$ using a isokinetic dynamometer does not produce accurate results. This suggestion was based on the evidence that one needed to accelerate the limb to achieve a pre-set angular velocity, therefore if the angular velocity was too high, a large part of the range of the motion would be used for the acceleration phase (Handel et al., 1996). Thus, in this study, $180 \text{ deg}\cdot\text{s}^{-1}$ was assumed to be a reasonable angular velocity to replicate the swimming situation. Also it was reported that the angular velocity of $60 \text{ deg}\cdot\text{s}^{-1}$ was an appropriate velocity to measure the peak torque and total work rather than higher angular velocity (Tredinnick and Duncan, 1988), and $60 \text{ deg}\cdot\text{s}^{-1}$ is one of the most widely accepted angular velocity to measure the peak torque of participants (McCleary and Andersen, 1992; Campenella et al., 2000; Lephart et al., 2002; Lund et al., 2005; Girold et al., 2006; Girold et al., 2007; Stickley et al., 2008). Thus $60 \text{ deg}\cdot\text{s}^{-1}$ was assumed to be the most appropriate angular velocity to assess the peak isokinetic torque in this study. Between the two different angular velocity trials, participants had 2 minutes rest, and there was at least 20 minutes rest between each shoulder rotation exercise.

Table 3. 3: Stroke frequency in front crawl at various speeds.

	Craig and Pendergast (1979)	Keskinen and Komi (1993)	McCabe & Sanders (2012)	
slow speed	26 cycles·min ⁻¹	27 cycles·min ⁻¹	-	-
moderate-sub maximum speed	-	39 cycles·min ⁻¹	41.3 cycles·min ⁻¹	38.6 cycles·min ⁻¹
fast speed	63 cycles·min ⁻¹	51 cycles·min ⁻¹	55.4 cycles·min ⁻¹	54.7 cycles·min ⁻¹

Table 3. 4: Stroke frequency in back crawl at various speeds.

	Craig and Pendergast (1979)	Smith et al. (1988)	Chollet et al. (2008)	
slow speed	22 cycles·min ⁻¹	-	-	24 cycles·min ⁻¹
moderate-sub maximum speed	-	34.6 cycles·min ⁻¹	30 cycles·min ⁻¹	-
fast speed	55 cycles·min ⁻¹	-	44.3 cycles·min ⁻¹	51 cycles·min ⁻¹

Table 3. 5: Mean angular speed of the hand around the shoulder (deg·s⁻¹) in front crawl at various speeds.

	Craig and Pendergast (1979)	Keskinen and Komi (1993)	McCabe & Sanders (2012)	
slow speed	156	162	-	-
moderate-sub maximum speed	-	234	247.8	231.6
fast speed	378	306	332.4	328.2

Table 3. 6: Mean angular speed of the hand around the shoulder (deg·s⁻¹) in back crawl at various speeds.

	Craig and Pendergast (1979)	Smith et al. (1988)	Chollet et al. (2008)	Barbosa et al. (2008)
slow speed	132	-	-	144
moderate-sub maximum speed	-	207.6	180	-
fast speed	300	-	265.8	306

3.5.1.2. The Testing Protocol for 3D Kinematic Data Collection

The same procedure used in Study 2 was used in Study 3. The testing protocol was four times 50m swims at the speed of 130% *vOBLA*, 122% *vOBLA*, 115% *vOBLA*, 107% *vOBLA* with four minutes rest. The only difference between the protocols in Study 2 and Study 3 were that the testing speeds in Study 3 were based on *vOBLA* of each stroke, instead of back crawl speeds, to ensure the later comparison in kinematics between the two strokes at the same exercise intensities.

3.5.2. Data Collection

The isokinetic torque (N·m) data using BIODEX dynamometer was automatically saved in the computer connected with the isokinetic dynamometer. In the software, the peak torque (N·m), peak torque per body mass (%), mean peak torque (average of peak torque values in each repetition: N·m), total work (J) were automatically calculated.

To obtain BSP data of the participants and the video data during the testing for the motion analysis, the same strategy as Study 1 and Study 2 was used (see 3.3.1 and 3.3.2).

3.5.3. Data Processing and Analysis

3.5.3.1. Isokinetic Data

After each testing session, the isokinetic data which was saved in the computer with the BIODEX software as PDF and text files were transferred to another computer to conduct correlation analysis with kinematic data from the swimming trials.

3.5.3.2. BSP Data and 3D Coordinates of the Swimming Trials

Photographs from E-zone testing, calibration video files, and the video files from the swimming testing were all treated using the same method of Study 1 and Study 2 to get anthropometric data of the participants and 3D coordinates for all swimming trials (see 3.3.3.2 and 3.3.3.3).

3.5.3.3. Calculation of Variables

COM displacement and speed, *SF*, *SL*, duration of each phase, body roll angles and 3D hand path distance relative to COM, were calculated by the same process as Study 1 and Study 2 (see 3.3.4). In this section, the kinematic variables calculated only in Study 3 are described.

3.5.3.3.1. Timing between Left and Right Strokes

The timing of the left and right hand strokes was assessed by observing the point of the entry of a wrist in relation to the relative time of the other arm stroke during the underwater phase (Timing index; Figure 3.6).

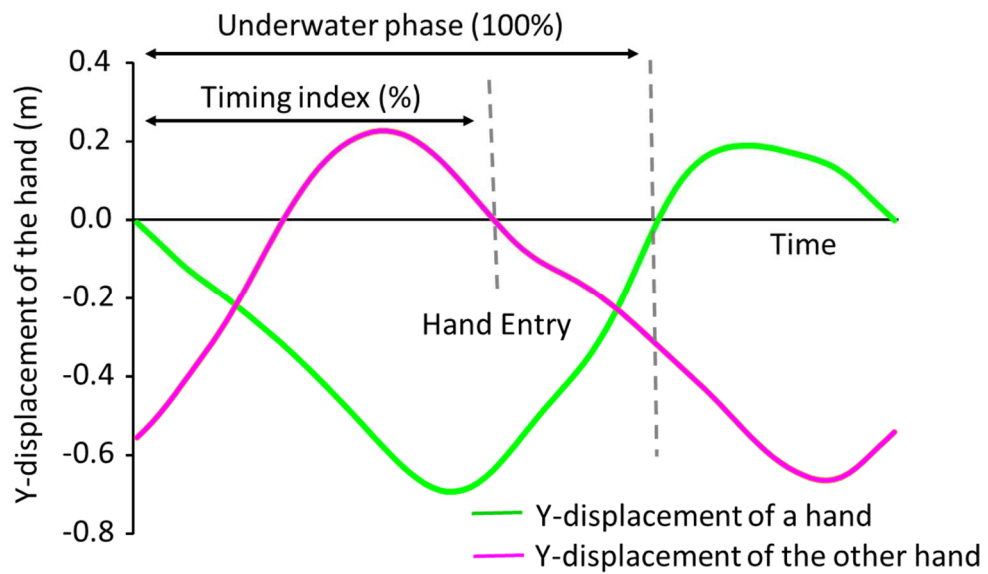


Figure 3. 6: Investigation of the coordination between left and right hand (Timing index).

3.5.3.3.2. Elbow Joint Angle

The elbow joint angle (θ_{Elbow}) was calculated by the following equation

$$\theta_{Elbow} = \text{acos} \left(\frac{Vec_{UA} \cdot Vec_{LA}}{|Vec_{UA}| |Vec_{LA}|} \right) \quad (\text{Equation 3. 10})$$

Where $Vec_{UA} \cdot Vec_{LA}$ is the dot product of the upper arm vector and lower arm vector, and $|Vec_{UA}|$ and $|Vec_{LA}|$ are the length of the upper arm vector and the lower arm vector respectively (Figure 3.7).

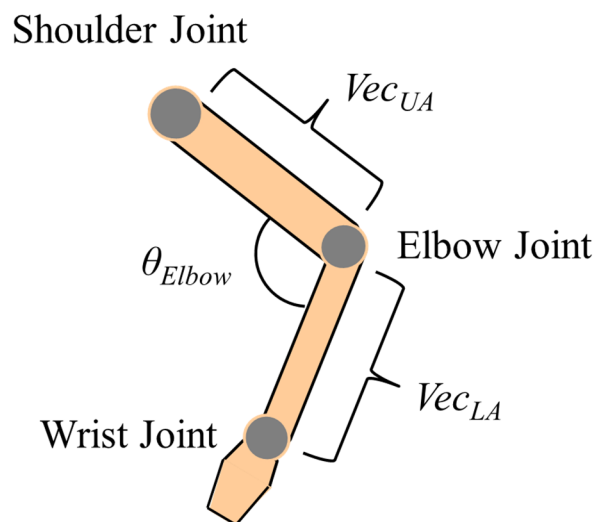


Figure 3. 7: Calculation of the elbow angle.

3.5.3.3.3. Shoulder Horizontal Abduction Angle

Shoulder horizontal abduction angle ($HAbd\theta_{SH}$) was calculated on the $x'-y'-z'$ which was transformed from original $x-y-z$ coordinate. In the $x'-y'-z'$ coordinates, the origin of the coordinate axis was the mid-point of left and right shoulders, and x' -axis was defined as the direction of the trunk-vector of the swimmer (the vector from the mid-point of left and right hip points toward the mid-point of left and right shoulder points).

$HAbd\theta_{SH}$ was calculated by Equation 3.11.

$$HAbd\theta_{SH} = \arccos\left(\frac{V_{y'z'SH} \cdot V_{y'z'UA}}{|V_{y'z'SH}| |V_{y'z'UA}|}\right) \quad (\text{Equation 3. 11})$$

Where $V_{y'z'SH} \cdot V_{y'z'UA}$ is the dot product of the shoulder vector and upper arm vector on the $y'-z'$ plane, and $|V_{y'z'SH}|$ and $|V_{y'z'UA}|$ are the length of the shoulder vector and the upper arm vector on the $y'-z'$ plane respectively (Figure 3.8).

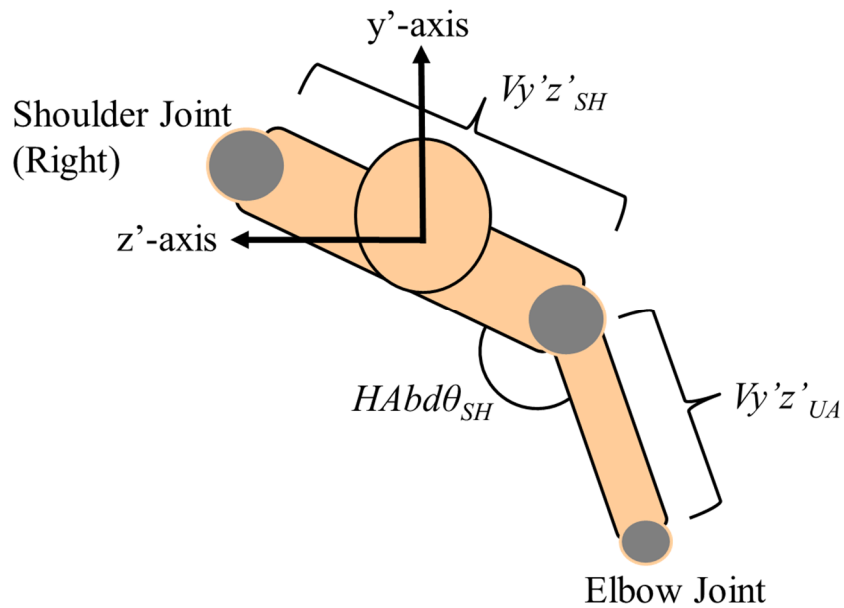


Figure 3. 8: Calculation of the shoulder horizontal abduction angle.

3.5.3.4. Correlation Analysis between Isokinetic Torque and Swimming Performance

The correlations between the values from isokinetic torque measurement (peak torque per body weight and total work) and kinematic variables were examined to assess the effect of isokinetic torque of swimmers on swimming performance in front crawl and back crawl. The kinematic variables selected for the analysis were V_{mean} , SF , SL , SI , normalised SL (SL normalised by the height of the swimmer) and the duration of the underwater phase (the total duration of the entry, pull, push, and release phase) in the 130% $vOBLA$ trials of front crawl and back crawl. This was based on the rationale that the participants performed isokinetic torque measurements with maximum effort, and thus, to conduct correlation analysis between the isokinetic torque and only maximum effort swimming (i.e. 130% $vOBLA$ trials) was appropriate. Both left and right isokinetic torque data was used for the correlation analysis, and the kinematic variables which had significant correlations with both left and

right isokinetic torque values were considered to be significant to minimise the error due to the small sampling number (N=10).

3.6. Statistical Analysis in Study 2 and Study 3

To investigate the differences in kinematic variables between front crawl and back crawl in Study 2 and Study 3, paired t-tests were conducted for each pair of the same speed trials and each pair of the same intensity trials. Prior to the t-tests, normality was checked using Kolmogorov–Smirnov test, and Wilcoxon signed-rank test, instead of paired t-test, was used when the normality was violated. For further investigation, *Cohen's d* was calculated for the difference in each variables.

To assess the main effect of the testing speed/intensity on the within-stroke change in kinematics, one-way repeated measures ANOVA was used. Prior to the testing, Mauchly's sphericity test was conducted. Sphericity is the extent which the variances of the differences between all combinations of related groups are equal. If the assumption wasn't met in the test, statistic results in which F-values were corrected by Greenhouse-Geisser procedure were used in this study (Field, 2007). Bonferroni post hoc tests were conducted when there was any significant main effect of the trial. Furthermore, effect size (ω^2) was calculated to show magnitude of the effect (Equation 3.12). It was considered that the ω^2 value of 0.01 represents small, 0.06 represents medium, and 0.14 represents large effect sizes respectively. For all the data,

$$\omega^2 = \frac{\left[\frac{k-1}{nk} (MS_M - MS_R) \right]}{MS_R + \frac{MS_B - MS_R}{k} + \left[\frac{k-1}{nk} (MS_M - MS_R) \right]}$$

(Equation 3. 12)

Where k is the number of conditions in the testing, n is the number of participants, MS_M is the mean square for the model, MS_R is the residual mean square, MS_B is the mean square which is been able to obtain using the equation below.

$$MS_B = \frac{SS_T - SS_M - SS_R}{n-1} \quad (\text{Equation 3. 13})$$

Where SS_T is the total sum of square, SS_M is the model sum of square, and SS_R is the residual sum of square.

Pearson product-moment correlations were conducted to assess the relationship between the values from the isokinetic torque testing and hand speed, SF , SL , and V_{mean} of the 130% $\nu OBLA$ trial in both front crawl and back crawl swimming testing. To conduct all these statistical analysis, IBM SPSS statistics 19 (IBM Corporation, Somers, NY, USA) was used. Statistical significance was set at $P < 0.05$.

Chapter Four
Results

In this chapter, accuracy and reliability of digitising and the results of Study 1, 2, and 3 are presented. Graphs and tables are used to visualise the results and to show the differences between front crawl and back crawl. Since there are large number of graphs and tables, this chapter is divided into five sub-chapters, and some graphs and tables are shown in appendix. All results from post-hoc tests are also presented in appendix.

It should also be reminded that in the results, hand and foot data are based on wrist and ankle kinematics, and not the mid-points of hand and foot segments.

Chapter Four-One

Accuracy, Reliability and Testing Speeds of the Studies

4.1. Accuracy, Reliability and Testing Speeds of the Studies

4.1.1. Accuracy and Reliability of the Data Processing

4.1.1.1. Reliability of Investigator's Digitising

Table AP.1 and Table AP.2 in Appendix present the results from the reliability assessment, which was based on the same stroke cycle (one stroke cycle from a front crawl trial, and one stroke cycle from a back crawl trial) digitised five times for each front crawl and back crawl trial. The standard deviation values were smaller or similar compared with previous studies' results for most variables (McCabe et al., 2011; Sanders and Psycharakis, 2009).

However, the coefficient of variation (*CV*) of the intra-cyclic velocity variation in both front crawl and back crawl were relatively larger than other variables (front crawl: 10.99%, back crawl: 8.43%). Other variables which had *CV* of over 5% in both front crawl and back crawl were net impulse (front crawl: 7.91%, back crawl: 9.36%) and yaw angle fluctuation (front crawl: 5.66%, back crawl: 5.73%).

CV of the duration and 3D hand path distance of the release phase, and contribution of release phase on the total 3D hand speed were also quite large (20.0%, 11.1%, and 9.8% respectively).

4.1.1.2. Accuracy of Digitising at 25-Hz

The accuracy of 25-Hz digitising was assessed by comparing 10 different trials (5 back crawl, and 5 front crawl trials) with 25-Hz digitising frequency with the same trial with 50-Hz digitising frequency, which is commonly used digitising frequency in swimming studies (Figueiredo et al., 2013; McCabe et al., 2011; McCabe and Sanders, 2012; Psycharakis et al., 2010; Psycharakis and McCabe, 2011; Sanders and Psycharakis, 2009).

Table AP.3 and Table AP.4 in Appendix show the differences between 25-Hz and 50-Hz digitising trials (Table AP.3: back crawl, Table AP.4: front crawl). In both front crawl and back crawl, mean differences of most variables between 25-Hz and 50-Hz digitising trials were within 5%, except the net impulse during the propulsive phases (pull and push phases) in both front crawl and back crawl. However, the differences were smaller than the reliability error (digitise-redegitise error). Considering that the 50Hz trials 25Hz digitise were digitised separately, and thus the differences contain digitising error, smaller difference between 25Hz and 50Hz than reliability error suggest that the error caused by 25Hz digitise frequency instead of 50Hz digitise frequency should be small.

4.1.1.3. Summary of the Reliability Tests

In summary, the investigator's reliability tests showed small errors in most of the measured variables. However, intra-cyclic velocity variation, net impulse and yaw angle fluctuation had *CV* of larger than 5%. *CV* of the duration and 3D hand path distance of the release phase, and contribution of release phase on the total 3D hand speed were especially large.

The differences in the measured variables between 25-Hz and 50-Hz digitising were within 5% except the net impulse during the propulsive phases in both front crawl and back crawl.

4.1.2. Establishing Testing Speeds for Each Study

4.1.2.1. The Anaerobic Threshold and the Onset of Blood Lactate Accumulation

Figure 4.1 and Figure 4.2 show the relationship between the mean speed and blood lactate values ($[La^-]_b$) of the swimmers in each step of the 200m incremental back crawl (Figure 4.1) and front crawl (Figure 4.2) tests. Mean values of those at the anaerobic threshold (AnT) and the onset of blood lactate accumulation ($OBLA$) were also shown in the figures. Mean speeds at AnT and $OBLA$ were $1.10 \pm 0.04 \text{ m}\cdot\text{s}^{-1}$ and $1.16 \pm 0.06 \text{ m}\cdot\text{s}^{-1}$ in back crawl, and $1.25 \pm 0.07 \text{ m}\cdot\text{s}^{-1}$ and $1.28 \pm 0.06 \text{ m}\cdot\text{s}^{-1}$ in front crawl. Figure 4.3 shows $[La^-]_b$ at AnT of each participant. There was no significant difference in $[La^-]_b$ at AnT between front crawl and back crawl ($p=0.15$), and effect size showed medium value ($d=0.65$).

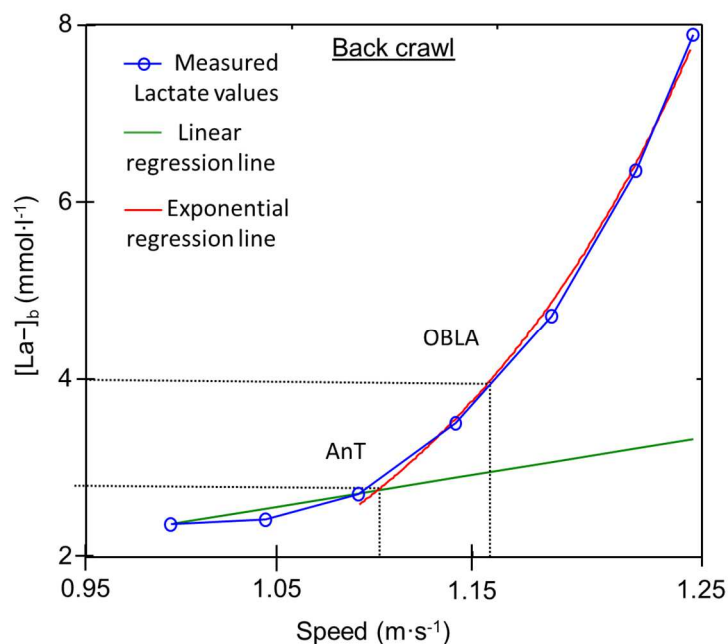


Figure 4. 1: Mean speeds and $[La^-]_b$ of the swimmers at each testing step (blue dots and line), AnT , and $OBLA$ in back crawl.

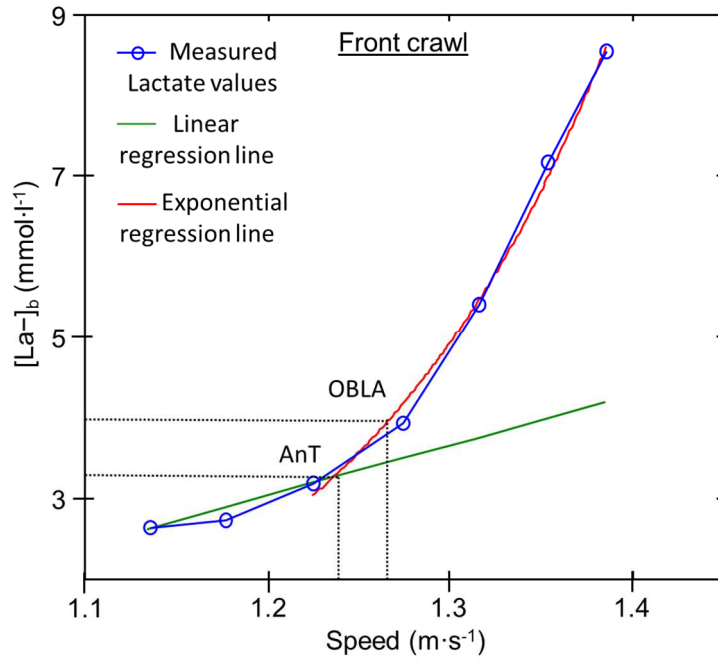


Figure 4. 2: Mean speeds and [La⁻]_b of the swimmers at each testing step (blue dots and line), AnT, and OBLA in front crawl.

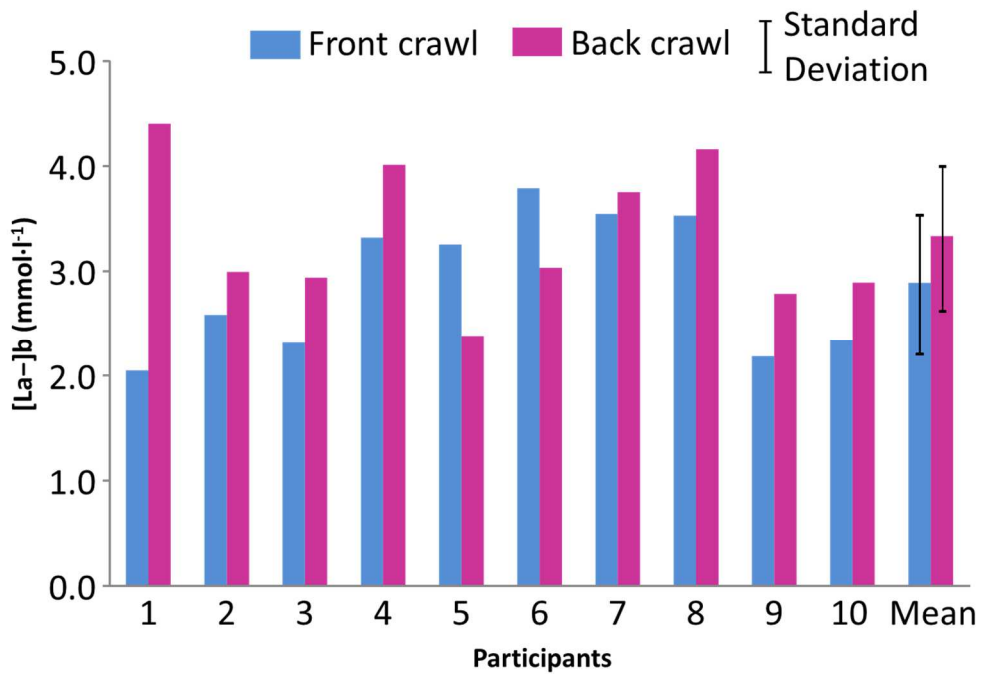


Figure 4. 3: [La⁻]_b at AnT of each swimmer in front crawl and back crawl.

4.1.2.2. Testing Speeds for Each Study

Table 4.1 shows 95% of v_{AnT} speed in back crawl (95% BC v_{AnT}) and estimated $OBLA$ speed (v_{OBLA}) at without-snorkel condition for both back crawl (BC $v_{OBLA-NS}$) and front crawl (FC $v_{OBLA-NS}$) of the swimmers. $v_{OBLA-NS}$ was assumed to be 105% of v_{OBLA} calculated from 7×200m testing results, since the snorkel makes swimmers' speed approximately 5% lower than the speed at non-snorkel condition (Barbosa et al., 2010).

For Study 1, testing speeds for both 300m front crawl and back crawl were 95% BC v_{AnT} .

For Study 2 and Study 3, the testing speeds of 4×50m testing were determined as 107%, 115%, 122%, and 130% of $v_{OBLA-NS}$ of each stroke. Testing speeds for all participants in all three studies are presented in Table AP.5 in Appendix.

Table 4. 1: 95% of v_{AnT} in back crawl, and 105% of v_{OBLA} ($v_{OBLA-NS}$: v_{OBLA} at without-snorkel condition) in front crawl and back crawl of each swimmer.

Participant	95% BC v_{AnT} ($m \cdot s^{-1}$)	BC $v_{OBLA-NS}$ ($m \cdot s^{-1}$)	FC $v_{OBLA-NS}$ ($m \cdot s^{-1}$)
1	1.03	1.24	1.43
2	1.01	1.20	1.39
3	1.03	1.17	1.42
4	1.02	1.21	1.27
5	1.01	1.14	1.30
6	1.05	1.23	1.31
7	1.12	1.28	1.32
8	1.04	1.15	1.28
9	1.08	1.33	1.41
10	1.04	1.24	1.37
Mean	1.04	1.22	1.35
SD	0.04	0.06	0.06

Chapter Four-Two

Results from Study 1

4.2. Results from Study1

4.2.1. Energy Expenditure

Figure 4.4 shows energy expenditure values of each participant in 300m front crawl and back crawl. All participants except participant 3 had higher energy expenditure values in back crawl than in front crawl. Mean energy expenditure of back crawl was significantly higher than front crawl ($44.12 \pm 2.24 \text{ mlO}_2 \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ and $37.96 \pm 2.85 \text{ mlO}_2 \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ respectively, $p < 0.01$). Effect size of the difference was also large ($d = 2.40$)

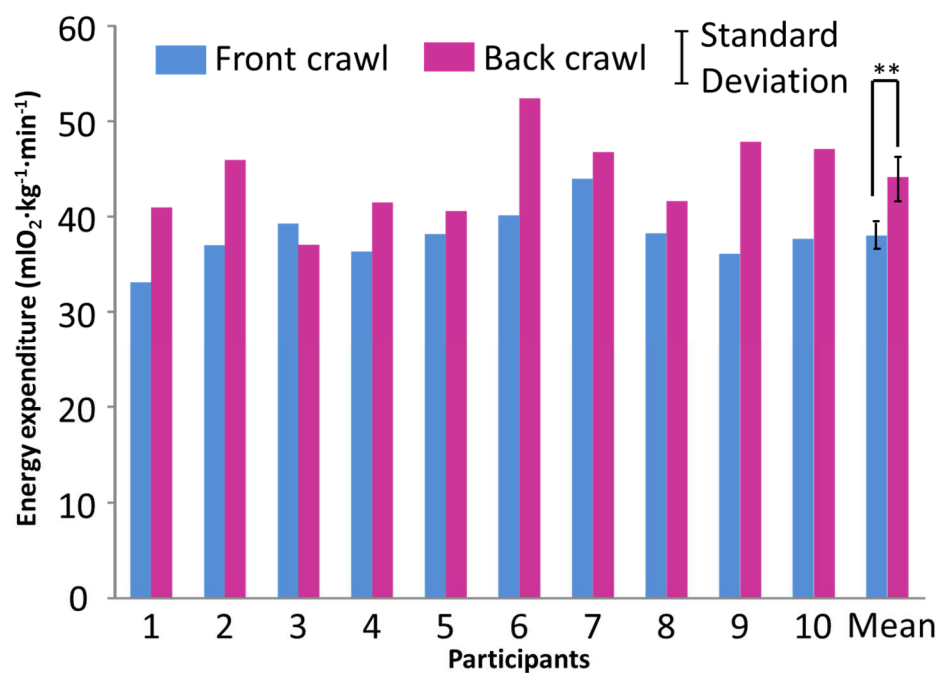


Figure 4. 4: Energy expenditure during 300m front crawl and 300m back crawl. Both strokes were performed at 95% of back crawl anaerobic threshold speed. The last two columns show mean values of each stroke. ** $p < 0.01$

4.2.2. Blood Lactate Values

Figure 4.5 shows the mean $[La^-]_b$ of the swimmers before and after the 300m front crawl and back crawl trials, as well as $[La^-]_b$ at *AnT*. In both front crawl and back crawl, $[La^-]_b$ before and after 300m trials was significantly lower than $[La^-]_b$ at *AnT*. Effect sizes of the differences between $[La^-]_b$ after 300m trials and $[La^-]_b$ at *AnT* were large (front crawl: $d=1.69$, back crawl: $d=1.31$). There was also a significant difference between $[La^-]_b$ before (1.77 \pm 0.28 mmol·l⁻¹) and after (2.24 \pm 0.36 mmol·l⁻¹) the 300m back crawl trial with a large effect size ($d=1.46$). There was no significant difference between $[La^-]_b$ before and after the 300m front crawl ($p=0.09$), and effect size of the difference was medium ($d=0.68$).

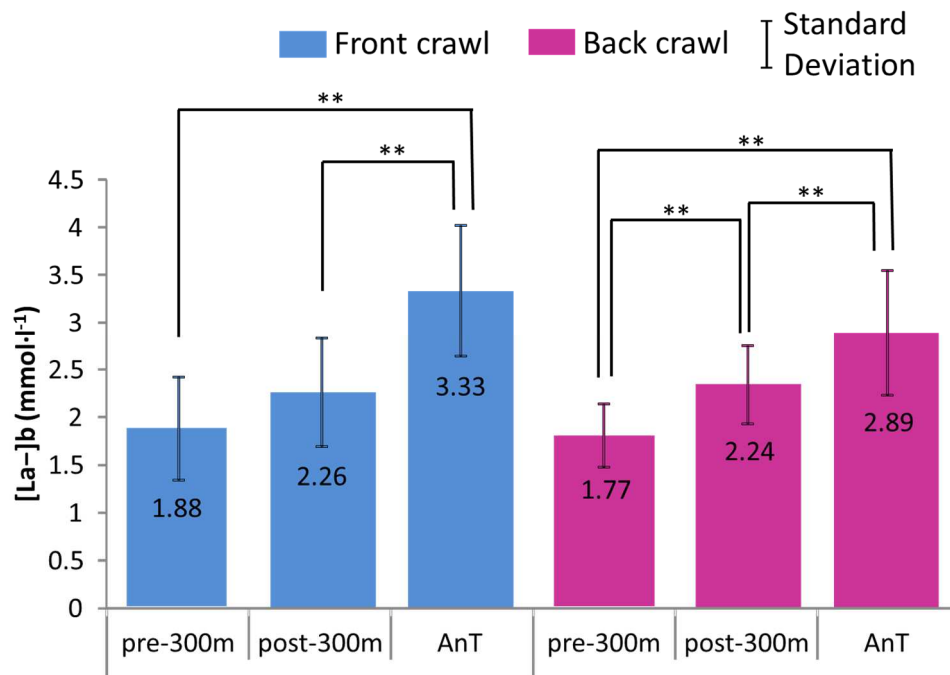


Figure 4. 5: $[La^-]_b$ before and after the 300m trials at 95% of the anaerobic threshold speed, and at the anaerobic threshold in front crawl and back crawl. ** $p < 0.01$

4.2.3. Race Parameters

Figure 4.6 shows mean stroke length (*SL*), stroke frequency (*SF*), stroke index (*SI*), and swimming speed (*V*) of the swimmers during the 300m trials. There were no significant differences between front crawl and back crawl in any of the four race parameters. (*SL*: $p=0.73$; *SF*: $p=0.12$; *SI*: $p=0.61$; *SV*: $p=0.12$). Effect sizes were small to medium for the differences in these four variables (*SL*: $d=0.18$; *SF*: $d=0.41$; *SI*: $d=0.25$; *V*: $d=0.43$).

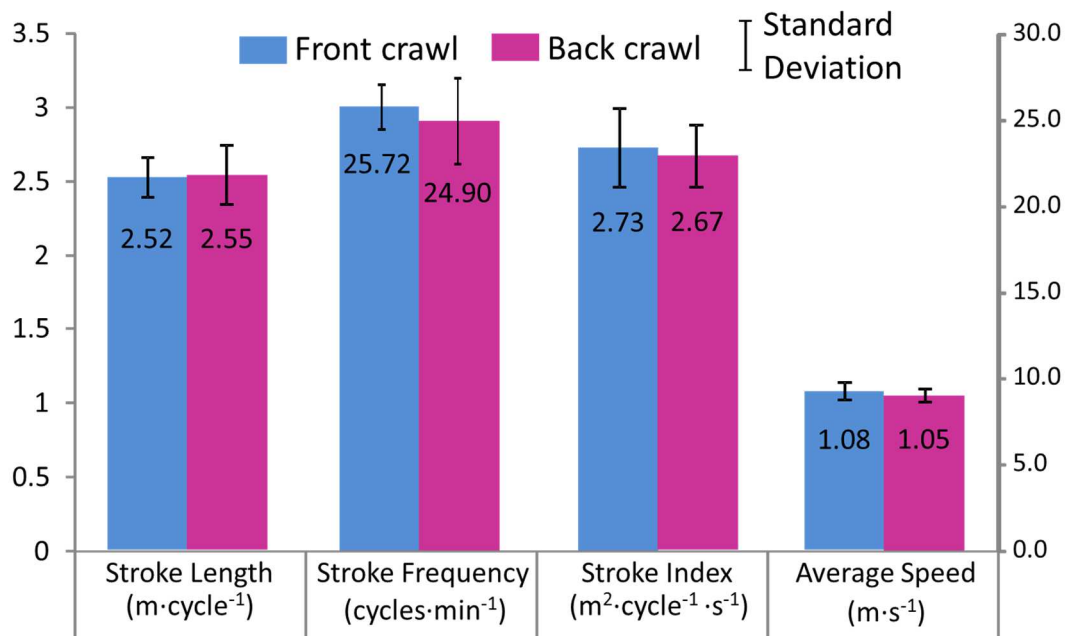


Figure 4. 6: Mean race parameters in front crawl and back crawl during 300m trials at the same speed (95% of back crawl anaerobic threshold speed).

4.2.4. 300m Time in Front Crawl and Back Crawl

Table 4.2 shows the instructed time for 300m trials and the time the swimmers achieved in 300m front crawl and back crawl. There were no differences between the instructed time and the time of 300m front crawl and back crawl achieved by the swimmers, and the mean differences between the instructed time and 300m front crawl time and between instructed time and 300m back crawl time were 0.08 and 0.05 % respectively.

Table 4. 2: Instructed time and the time swimmers achieved in 300m front crawl and back crawl.

300m time	Instructed time	Front crawl	Back crawl
Time (s)	288.02 ±9.46	287.79 ±9.43	287.87 ±9.46
Difference from the instructed speed (%)	100	99.92 ± 0.30	99.95 ± 0.28

4.2.5. Duration of Stroke Phases

Figure 4.7 shows the duration of each phase of the upper limbs with respect to % stroke cycle time. The figure shows the mean duration of each phase in left and right arms. Front crawl spent significantly longer time in the entry phase than back crawl with a large effect size ($p < 0.01$, $d = 4.74$). On the other hand, the duration of the release phase and the above-water phase was significantly longer when swimming back crawl compared to front crawl ($p < 0.01$). Effect sizes of the differences in the release phase and the above-water phase were $d = 2.68$ and $d = 4.09$ respectively. There were no differences between the swimming strokes in terms of the pull and push phase durations with small effect sizes ($d = 0.00$ and $d = 0.20$ respectively).

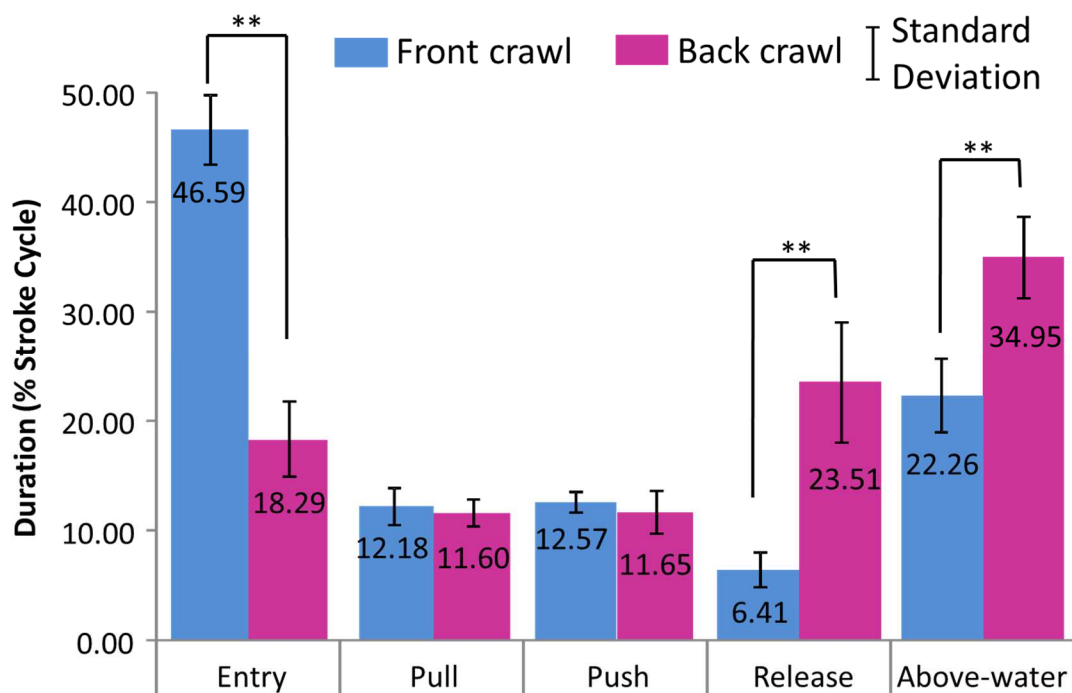


Figure 4. 7: Mean duration of each stroke phase in relation to the stroke cycle time in front crawl and back crawl during 300m trials at the same speed (95% of back crawl anaerobic threshold speed). ** $p < 0.01$

4.2.6. The Distance of the Hand Path

In the following sub-paragraphs, the hand path data during the stroke cycle and different stroke phases are presented. The hand path distance was calculated using the x, y, and z displacements of the wrist instead of the mid-point of the wrist and finger in this study.

4.2.6.1. Distance of the Hand Path during the Stroke Cycle

Figure 4.8 shows the hand path distance during the stroke cycle in front crawl and back crawl. Swimmers had significantly longer hand path distance in back crawl than in front crawl ($p < 0.01$) with a large effect size ($d = 2.57$).

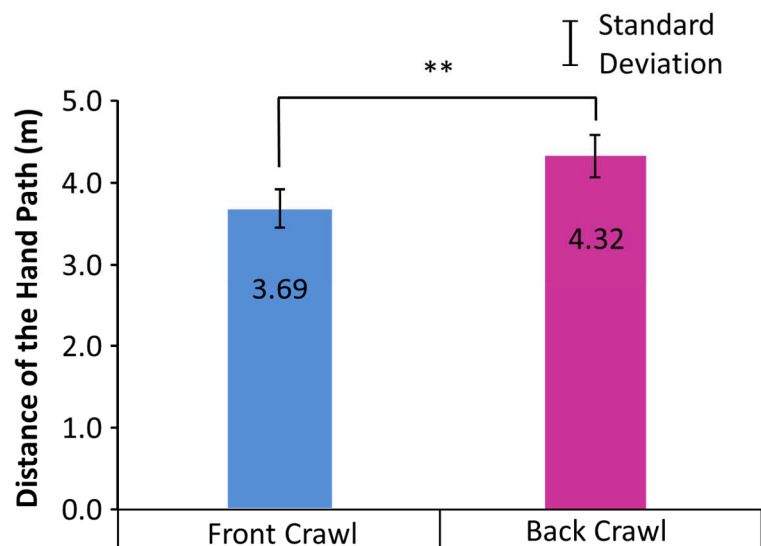


Figure 4. 8: Mean hand path distance during the stroke cycle in front crawl and back crawl during 300m trials at the same speed (95% of back crawl anaerobic threshold speed). ** $p < 0.01$

4.2.6.2. Distance of the Hand Path during Each Phase

Figure 4.9 shows the distance of the hand path during each in front crawl and back crawl.

There were no significant differences in the distance of the hand path during the pull and push phases. However, swimmers had longer hand path distance during the entry phase, and shorter hand path distance during the release and above water phase in front crawl than in back crawl ($p < 0.01$).

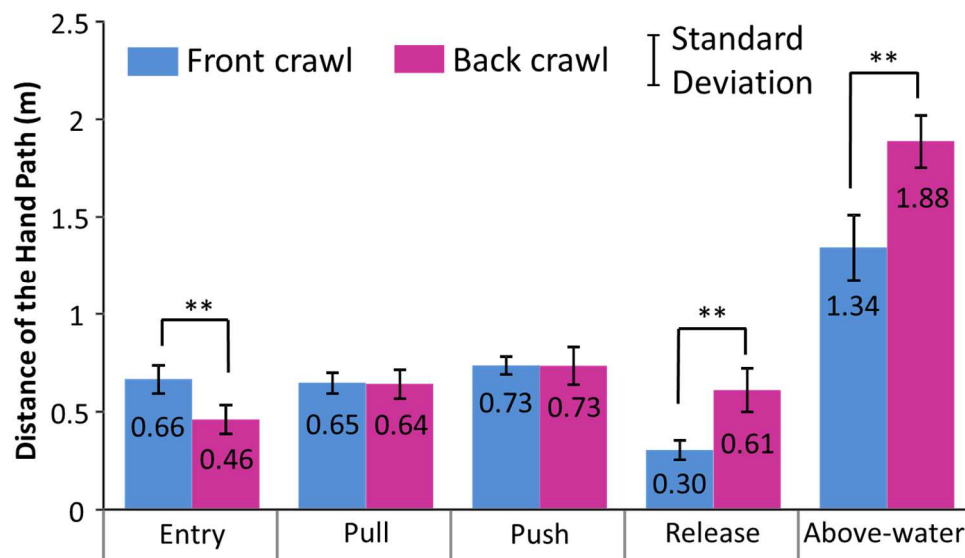


Figure 4. 9: Mean hand path distance during each phase in front crawl and back crawl during 300m trials at the same speed (95% of back crawl anaerobic threshold speed). ** $p < 0.01$

4.2.6.3. The Distance of the Hand Path during Underwater Non-Propulsive Phases

Figure 4.10 shows the distance of the hand path during underwater non-propulsive phases (sum of the distance of the hand path during the entry and release phases). Swimmers had significantly longer hand path distance in back crawl than in front crawl ($p < 0.01$) with a large effect size ($d = 1.00$).

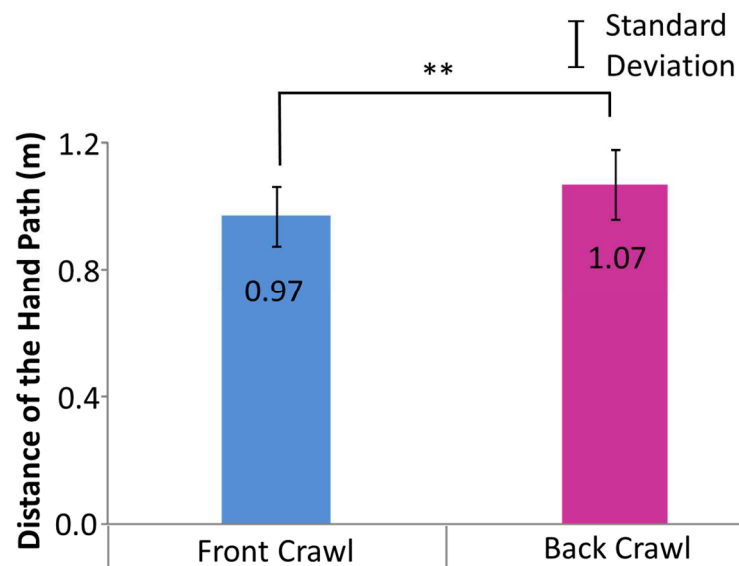


Figure 4. 10: Mean hand path distance during underwater non-propulsive phases in front crawl and back crawl during 300m trials at the same speed (95% of back crawl anaerobic threshold speed). ** $p < 0.01$

4.2.7. Hand Speed and Acceleration Relative to the Water

In the following sub-paragraphs, the hand speed and acceleration in different stroke phases are presented. The presented data are based on the speed and acceleration of the wrist, rather than the mid-point of the wrist and finger.

4.2.7.1. Hand Speed Relative to the Water in Swimming Direction during the Pull and Push Phases

Figure 4.11 shows the mean hand speed relative to the water in swimming (x) direction during the pull and push phases. The presented values are mean values of right and left hands. There were no significant differences in mean hand speed during the two phases, however, the effect sizes of the differences were nearly large and large ($d=0.78$, and $d=1.18$, respectively).

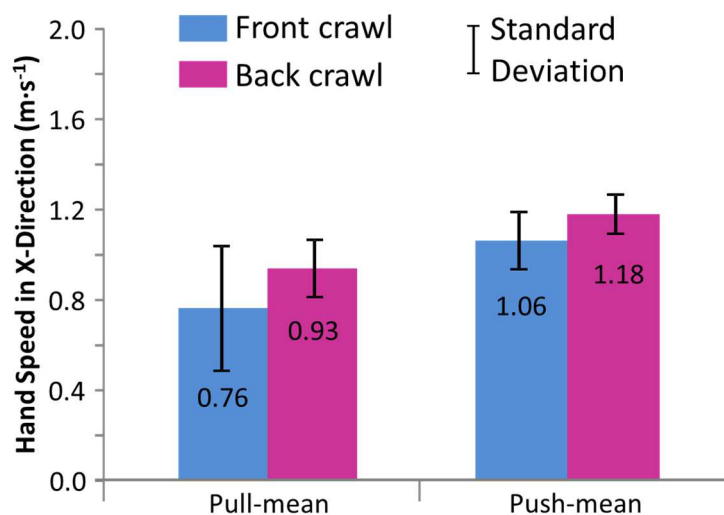


Figure 4. 11: Mean hand speed in the swimming direction during the pull and push phases in front crawl and back crawl during 300m trials at the same speed (95% of back crawl anaerobic threshold speed).

4.2.7.2. Hand Acceleration Relative to the Water in the Swimming Direction during the Pull and Push Phases

Figure 4.12 shows the mean hand acceleration in swimming (x) direction relative to the water during the pull and push phases. Swimmers had significantly larger acceleration in back crawl than in front crawl during the pull phase with a large effect size ($p < 0.01$, $d = 2.8$). On the other hand, swimmers had significantly larger deceleration during the push phase in back crawl than in front crawl with a large effect size ($p < 0.01$, $d = 1.51$).

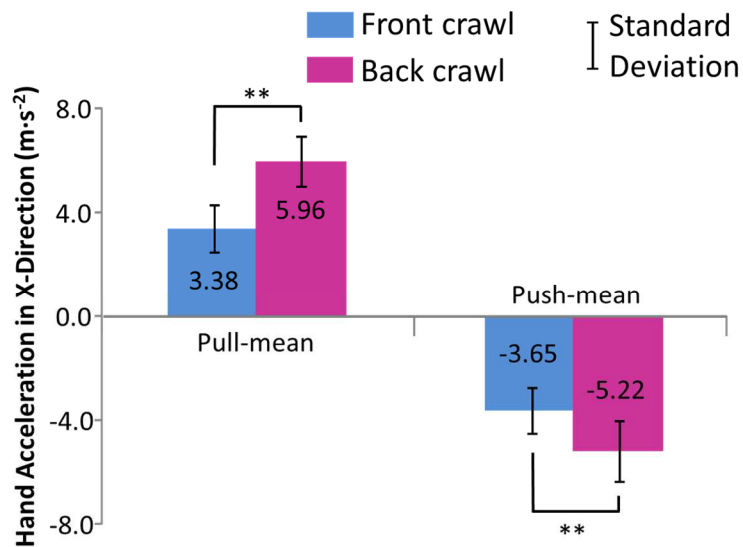


Figure 4. 12: Mean hand acceleration and deceleration in the swimming direction during the pull and push phases in front crawl and back crawl during 300m trials at the same speed (95% of back crawl anaerobic threshold speed). ** $p < 0.01$

4.2.7.3. Hand Speed Relative to the Water in Vertical and Lateral Directions during the Underwater Phases

Figure 4.13 shows the mean hand speed in vertical and lateral directions (Y and Z directions) during underwater phases (sum of the entry, pull, push, and release phases). There was no significant difference in the mean hand speed in the vertical direction and the effect size was small ($d=0.31$). On the other hand, the mean hand speed in the lateral direction in back crawl was significantly larger than that in front crawl with a large effect size ($p<0.01$, $d=5.52$).

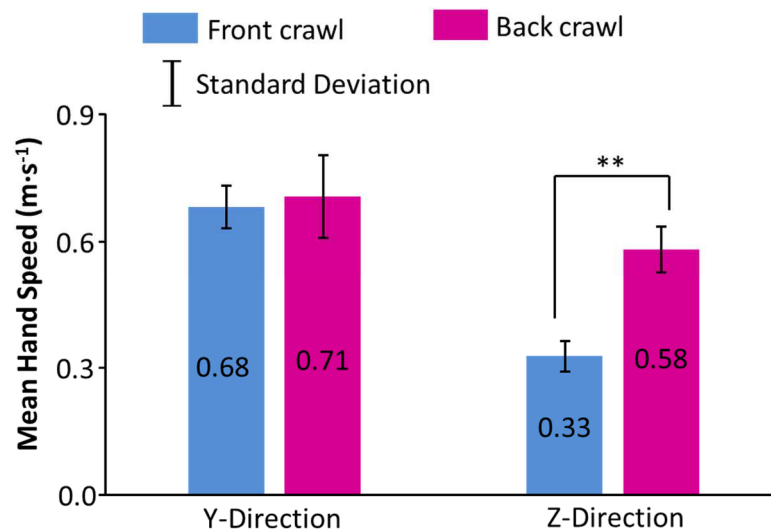


Figure 4. 13: Mean hand speed during the underwater phases in vertical (Y) and lateral (Z) directions in front crawl and back crawl during 300m trials at the same speed (95% of back crawl anaerobic threshold speed). ** $p<0.01$

4.2.7.4. Mean 3D Hand Speed Relative to the Body of the Swimmer

Figure 4.14 shows the mean 3D hand speed relative to the body of the swimmer during the stroke cycle in front crawl and back crawl. Swimmers had significantly faster 3D hand speed in back crawl than in front crawl ($p < 0.01$) with a large effect size ($d = 2.21$).

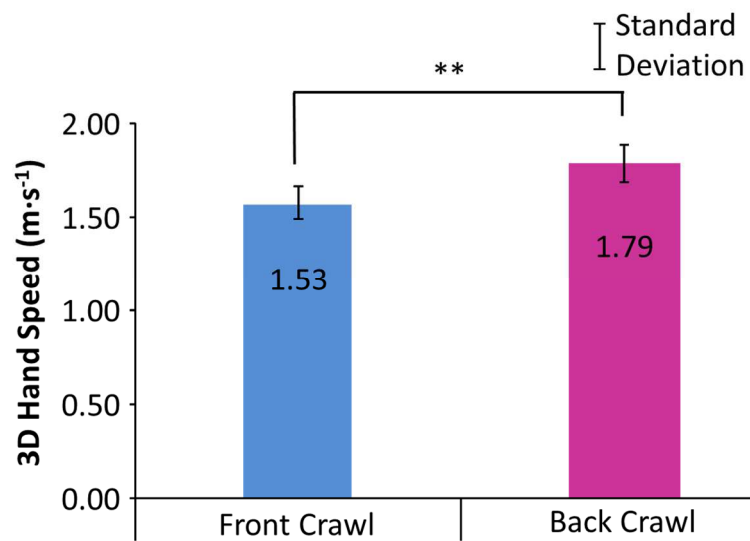


Figure 4. 14: Mean 3D hand speed during the stroke cycle in front crawl and back crawl during 300m trials at the same speed (95% of back crawl anaerobic threshold speed). ** $p < 0.01$

4.2.8. Froude Efficiency

Figure 4.15 shows Froude efficiency of the swimmers in front crawl and back crawl. Swimmers had significantly higher Froude efficiency in front crawl than in back crawl ($p < 0.01$) with a large effect size ($d = 3.00$).

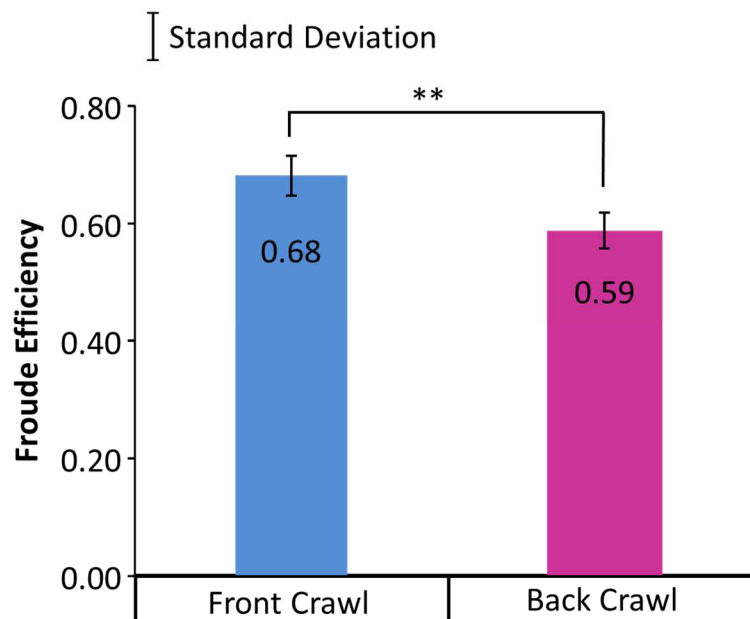


Figure 4. 15: Mean Froude efficiency in front crawl and back crawl during 300m trials at the same speed (95% of back crawl anaerobic threshold speed). ** $p < 0.01$

4.2.9. Foot Path Distance

Figure 4.16 shows the foot path distance (based on ankle path distance) during the stroke cycle in front crawl and back crawl. Swimmers had significantly longer foot path distance in back crawl than in front crawl ($p < 0.01$) with a larger effect size ($d = 1.28$).

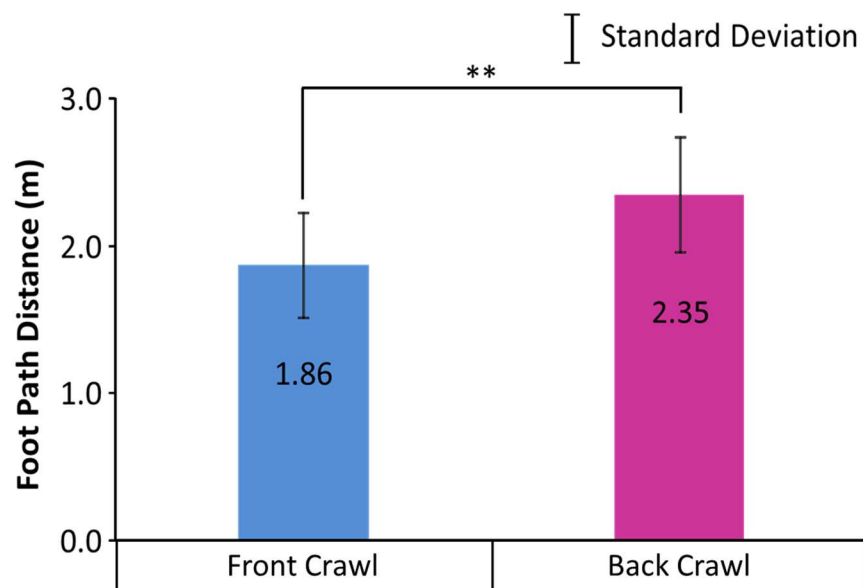


Figure 4. 16: Foot path distance during the stroke cycle in front crawl and back crawl during 300m trials at the same speed (95% of back crawl anaerobic threshold speed). ** $p < 0.01$

4.2.10. Mean 3D Foot Speed

Figure 4.17 shows the mean 3D foot speed during the stroke cycle (based on ankle 3D speed) in front crawl and back crawl. Swimmers had significantly faster 3D foot speed in back crawl than in front crawl ($p < 0.01$) with a large effect size ($d = 1.14$)

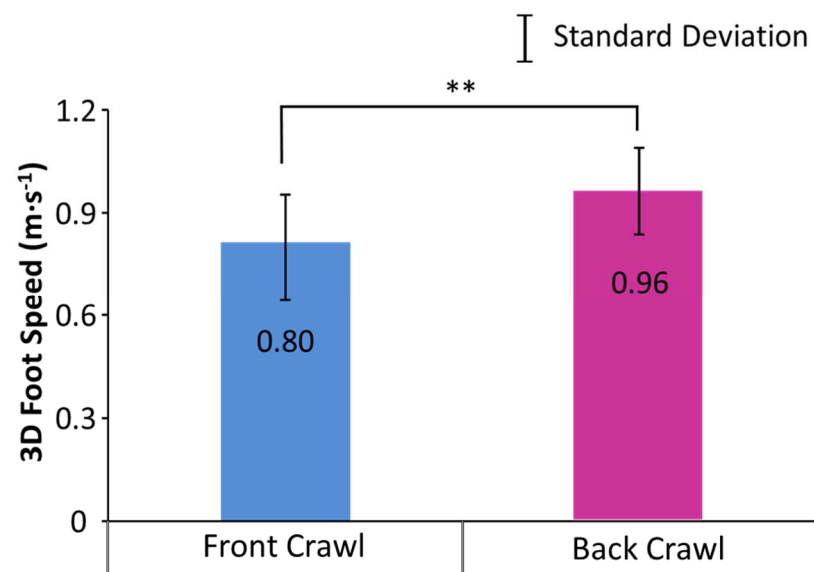


Figure 4. 17: Mean 3D Foot Speed during the stroke cycle in front crawl and back crawl during 300m trials at the same speed (95% of back crawl anaerobic threshold speed). ** $p < 0.01$

4.2.11. Range of Motion of the Foot

Figure 4.18 shows the range of motion of the foot (range of motion of the ankle) in vertical (y) and lateral (z) directions. The range of motion in vertical direction of the foot in back crawl was significantly larger than that in front crawl ($p < 0.01$) with a larger effect size ($d = 1.69$). However, there was no significant difference in the range of motion in lateral-direction between the strokes, and the effect size was medium ($d = 0.57$).

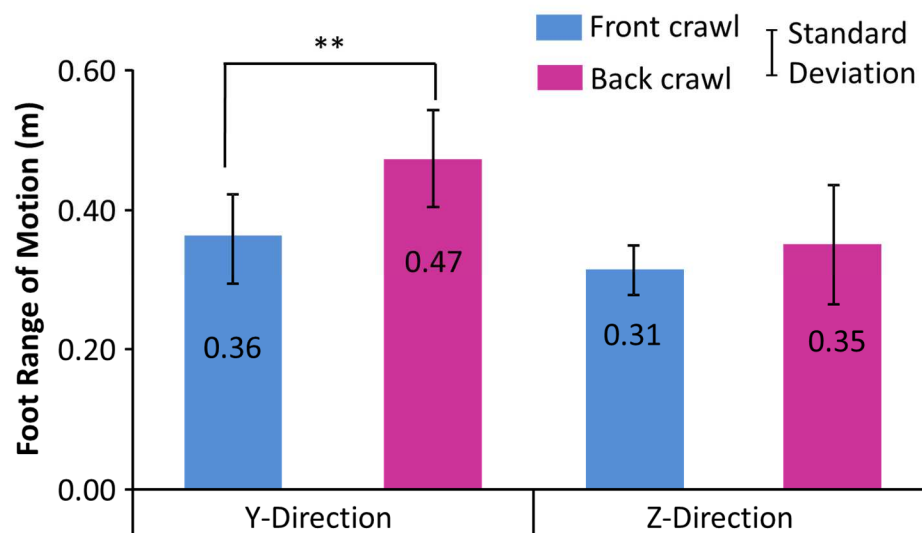


Figure 4. 18: Foot range of motion during the stroke cycle in vertical and lateral direction in front crawl and back crawl during 300m trials at the same speed (95% of back crawl anaerobic threshold speed). **($p < 0.01$)

4.2.12. Net Impulse during the Propulsive Phases

Figure 4.19 shows the net impulse during the propulsive phase (pull and push phases). There were no differences in the net impulse during the propulsive phases, and the effect size was small ($d= 0.18$).

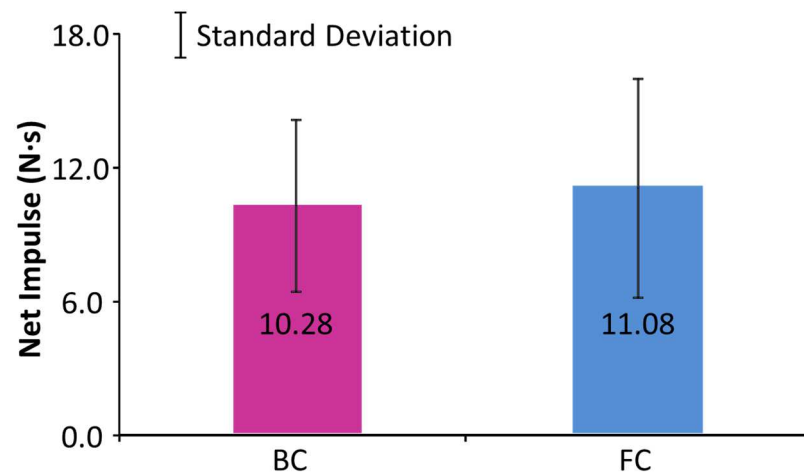


Figure 4. 19: Net impulse during the propulsive phases in front crawl and back crawl during 300m trials at the same speed (95% of back crawl anaerobic threshold speed).

4.2.13. Shoulder and Hip Maximum Roll Angles

Figure 4.20 shows maximum shoulder and hip roll angles. Swimmers had larger roll maximum angle in front crawl than in back crawl in both shoulder and hip. The p-values for these differences were significant at significance level of $p < 0.01$, and the effect sizes were large (shoulder roll: $d = 1.59$, hip roll: $d = 2.01$).

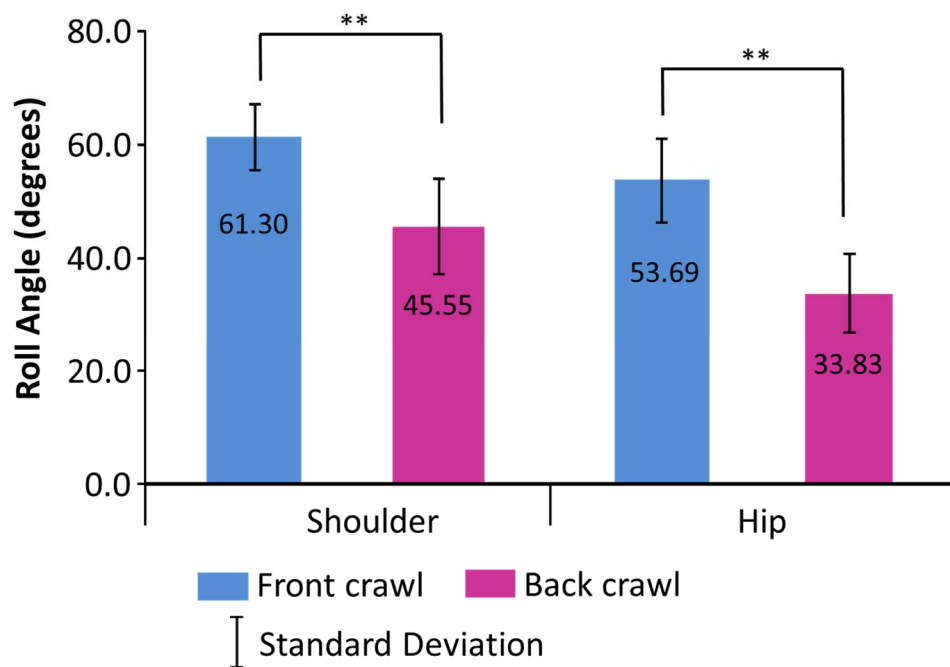


Figure 4. 20: Maximum shoulder and hip roll angles during the stroke cycle in front crawl and back crawl during 300m trials at the same speed (95% of back crawl anaerobic threshold speed). ** $p < 0.01$

4.2.14. Yaw Angle Fluctuation

Figure 4.21 shows the yaw angle fluctuation (the difference between maximum and minimum yaw angle) in front crawl and back crawl. There was no significant difference between the strokes. However, the effect size of the difference was large ($d=0.83$).

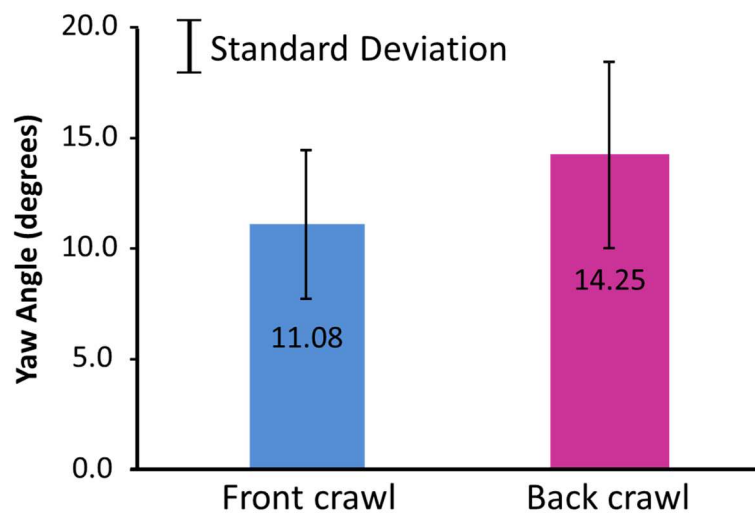


Figure 4. 21: Yaw angle fluctuation during the stroke cycle in front crawl and back crawl during 300m trials at the same speed (95% of back crawl anaerobic threshold speed).

4.2.15. Maximum Lateral Distance between Hand and the Centre of Mass (COM)

Figure 4.22 shows the maximum lateral distance between hand and the centre of mass (COM) in lateral-direction during the stroke cycle. Swimmers had significantly longer maximum lateral distance between the hand COM in back crawl than in front crawl ($p < 0.01$) with larger effect sizes (Left: $d = 2.87$, Right: $d = 2.39$).

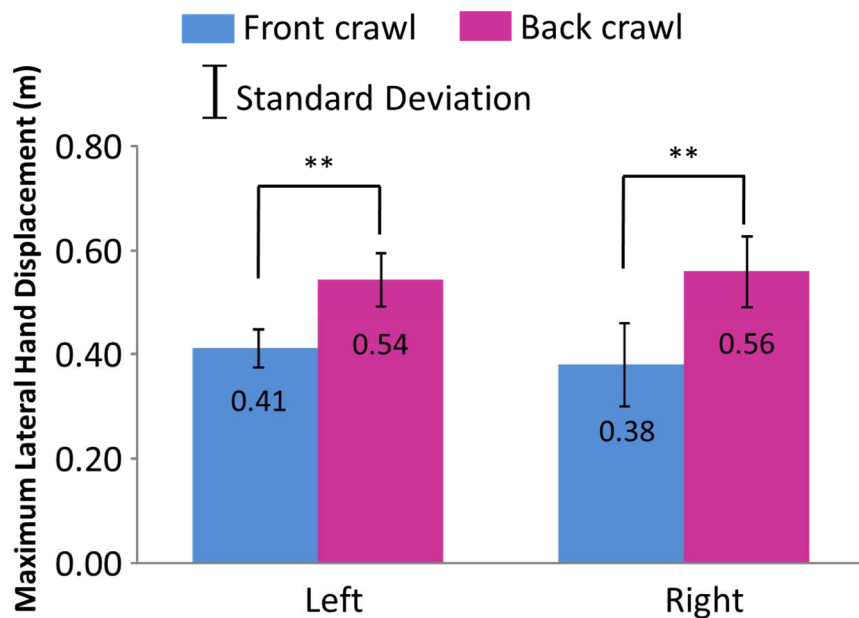


Figure 4. 22: Maximum distance between the hand and the centre of mass in lateral-direction during the stroke cycle in front crawl and back crawl during 300m trials at the same speed (95% of back crawl anaerobic threshold speed). ** $p < 0.01$

4.2.16. Intra-Cycle Velocity in the Swimming Direction

4.2.16.1. Intra-Cycle Maximum and Minimum Velocity

Figure 4.23 shows Intra-cycle maximum and minimum velocity in the swimming direction of swimmers' COM during a stroke cycle (IV_{max} and IV_{min} respectively) in front crawl and back crawl. There were no differences between these strokes in both IV_{max} and IV_{min} , and effect sizes were small and medium (IV_{max} : $d=0.02$, IV_{min} : $d=0.52$).

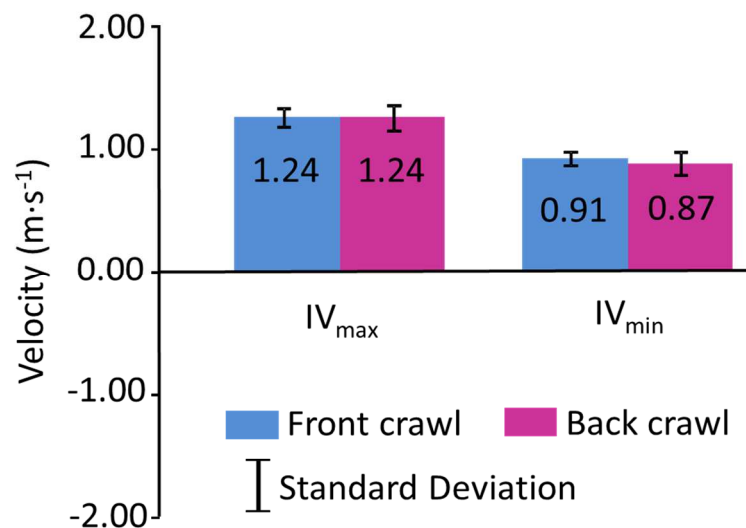


Figure 4. 23: Intra-cycle Maximum and minimum velocities during the stroke cycle in front crawl and back crawl during 300m trials at the same speed (95% of back crawl anaerobic threshold speed).

4.2.16.2. Intra-Cycle Velocity Variation in the Swimming Direction

Figure 4.24 shows intra-cycle velocity variation in the swimming direction (IVV_x) in front crawl and back crawl. There was no significant difference between the strokes, and the effect size of the difference was medium ($d=0.61$).

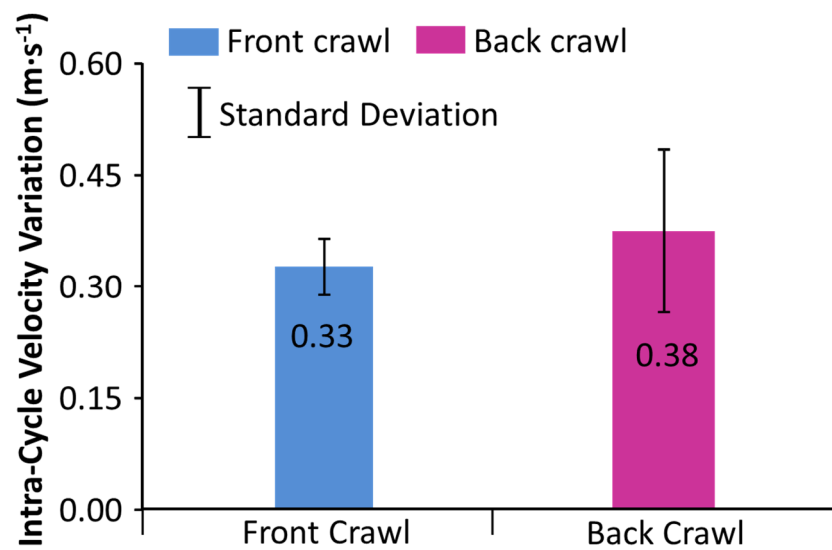


Figure 4. 24: Intra-cycle velocity variation in the swimming direction in front crawl and back crawl during 300m trials at the same speed (95% of back crawl anaerobic threshold speed). ** $p<0.01$

4.2.17. Vertical Displacement

4.2.17.1. COM Displacement in Vertical Direction

Figure 4.25 shows the mean, maximum, and minimum vertical displacement of the COM during front crawl and back crawl. The mean and maximum vertical displacement of COM were smaller (deeper in relation to the water surface) in back crawl than in front crawl (mean COM vertical displacement: $p < 0.02$, maximum COM vertical displacement: $p < 0.01$). The size of the effects were nearly large ($d = 0.79$) in the mean displacement and large ($d = 1.18$) in the maximum displacement. On the other hand, there was no significant difference in the minimum COM displacement and the effect size was small ($d = 0.33$).

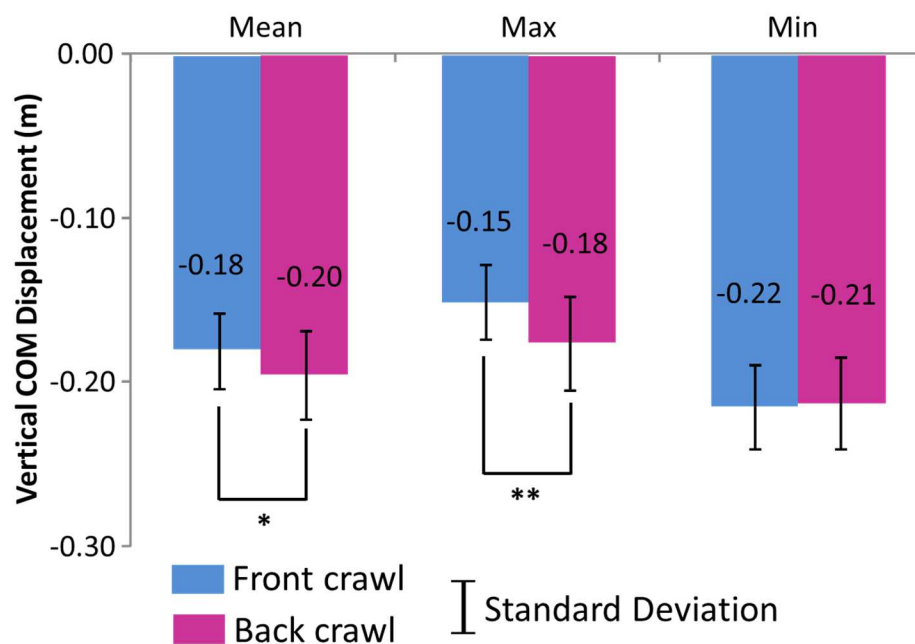


Figure 4. 25: Mean, maximum, and minimum vertical COM displacement during the stroke cycle in front crawl and back crawl during 300m trials at the same speed (95% of back crawl anaerobic threshold speed). * $p < 0.02$, ** $p < 0.01$

4.2.17.2. Mean Vertical Displacement of Shoulder, Hip, Knee, and Foot.

Figure 4.26 shows the mean vertical displacement of shoulder, hip, knee, and foot (middle point of right and left shoulder and hip, and mean value of left and right knees and foot).

There was no difference between front crawl and back crawl in the mean vertical displacement of the middle-hip and knee. However, swimmers had significantly higher displacement of the middle-shoulder and foot in front crawl than in back crawl with large effect sizes (middle-shoulder: $p < 0.01$ and $d = 1.00$, foot: $p < 0.01$, $d = 2.16$).

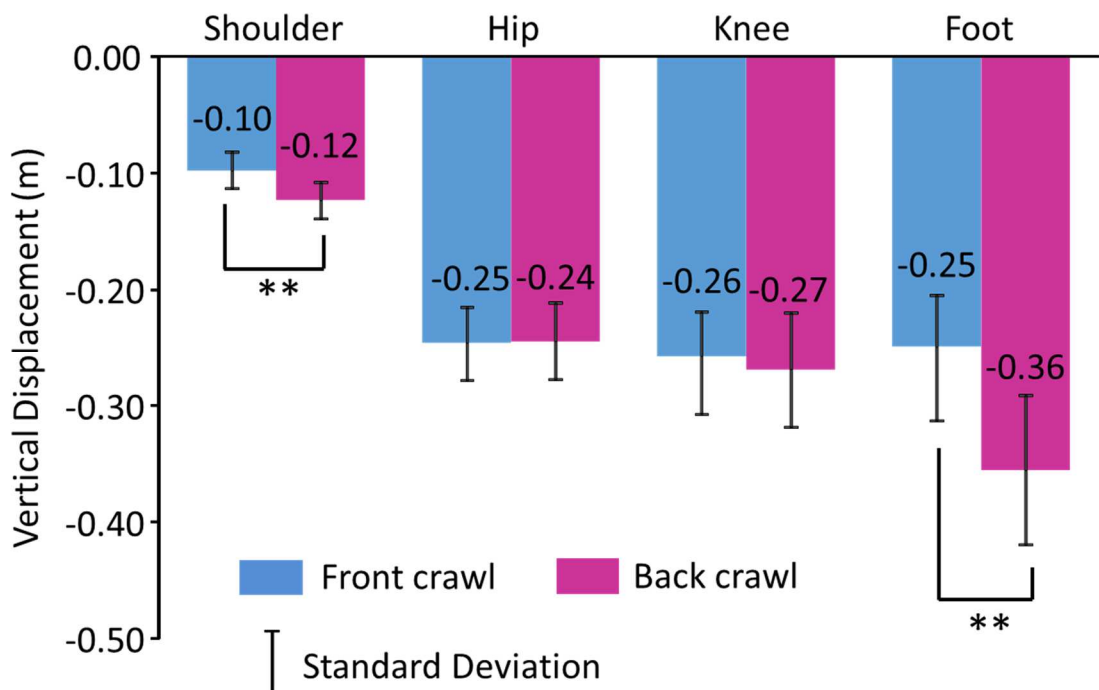


Figure 4. 26: Mean vertical displacement of mid-shoulder, mid-hip, knee, and foot during the stroke cycle in front crawl and back crawl at 95% of the anaerobic threshold speeds. ** $p < 0.01$

Chapter Four-Three

Results from Study 2

4.3. Results from Study 2

In this section, the results from 4×50-m trials in front crawl and back crawl at the same testing speeds are presented. In all text, figures and tables, ‘trial-1’ is the slowest trial and ‘trial-4’ is the fastest trial in the four trials.

4.3.1. Race Parameters

4.3.1.1. Mean Speed of the COM

Figure 4.27 shows V of back crawl (BC) trials and V of front crawl at back crawl speed (FC@BC) trials. There were no differences between BC and FC@BC in any trials, and effect size showed small values (trial-1: $d=0.32$, trial-2: $d=0.49$, trial-3: $d=0.45$, trial-4: $d=0.26$). The main effect of trials on the speed in FC@BC was significant ($p<0.01$). Effect size of the main effect was large ($\omega^2=0.60$).

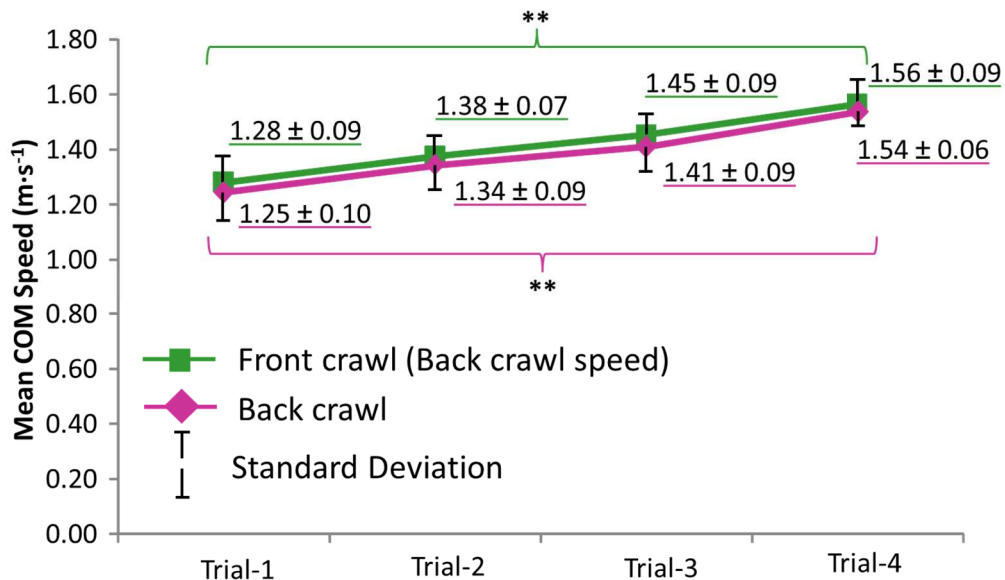


Figure 4. 27: Mean COM speeds of the swimmers at four times 50-m front crawl at the back crawl speed, and back crawl. ** $p<0.01$

4.3.1.2. Stroke Frequency

Figure 4.28 shows *SF* at the 4×50-m trials in BC and FC@BC. *SF* of BC in trial-3 was a significantly higher than that of FC@BC ($p<0.02$) with medium effect size ($d=0.55$).

Although there were no significant differences between BC and FC@BC in other trials, effect sizes of trial-2 and trial-4 showed *SF* in BC in those trials were higher than those in FC@BC with medium size of effects (trial-2, $d=0.51$; trial-4, $d=0.48$). On the other hand, the effect size of trial-1 was small ($d=0.27$). The main effect of trials on *SF* was significant in FC@BC ($p<0.01$), and the effect size was large ($\omega^2=0.65$).

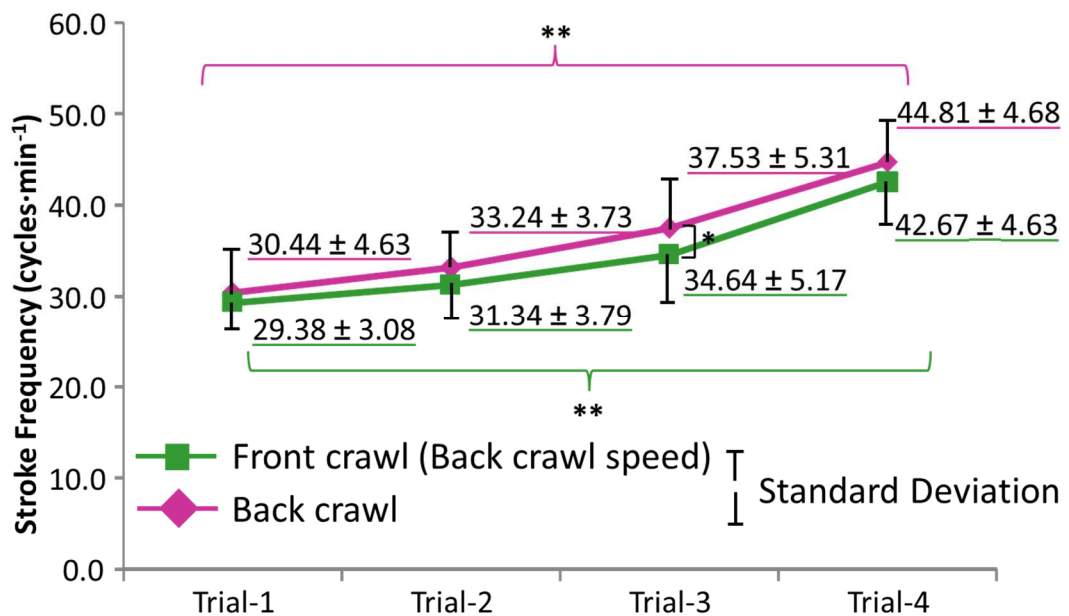


Figure 4. 28: Stroke frequency at four times 50-m trials in back crawl and front crawl at the same testing speeds. ** $p<0.01$, * $p<0.02$

4.3.1.3. Stroke Length

Figure 4.29 shows *SL* of BC and FC@BC at the four times 50m-trials. *SL* of FC@BC was significantly longer than that of BC at trial-2, trial-3, and trial-4 with large effect sizes (trial-2: $p<0.02$, $d=1.05$, trial-3: $p<0.01$, $d=1.15$, trial-4: $p<0.02$, $d=0.85$). Although there was no significant difference between FC@BC and BC at trial-1, swimmers had longer *SL* in FC@BC than that in BC with medium-large effect size ($d=0.71$). There was significant main effect of trials on *SL* in FC@BC ($p<0.01$), and the size of the effect was large ($\omega^2=0.41$).

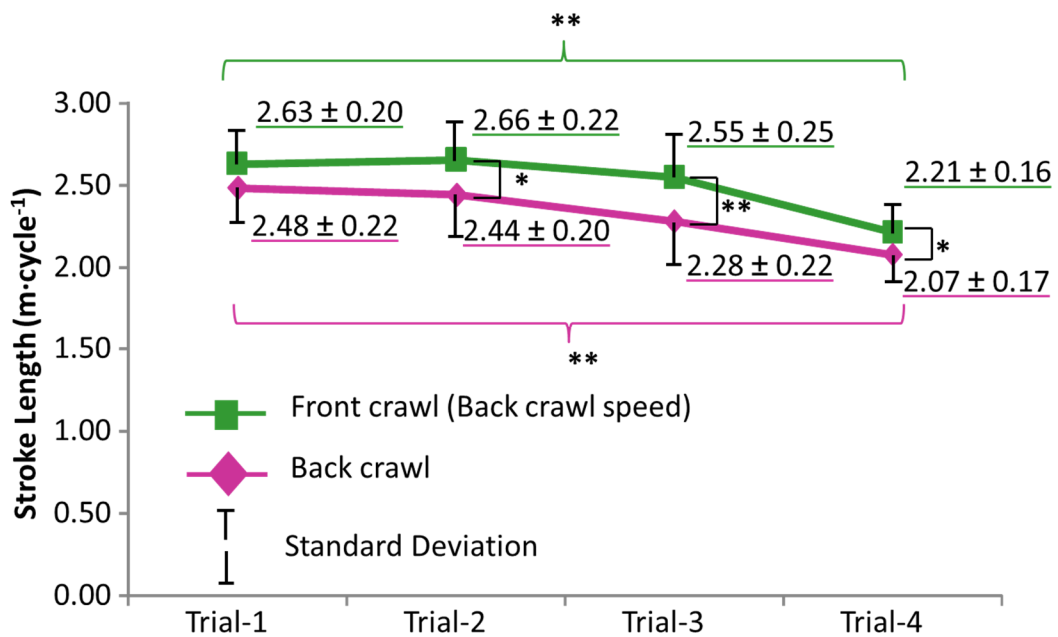


Figure 4. 29: Stroke length at four times 50-m trials in back crawl and front crawl at the same testing speeds. ** $p<0.01$, * $p<0.02$

4.3.1.4. Stroke Index

Figure 4.30 shows *SI* of BC and FC@BC. *SI* in FC@BC was significantly larger than that in BC in all four trials (trial-1: $p < 0.05$, trial-2: $p < 0.02$, trial-3: $p < 0.01$, trial-4: $p < 0.02$), with large effect sizes ($d = 1.05$, $d = 1.21$, $d = 1.59$, and $d = 1.12$ respectively). In FC@BC trials, there was a significant main effect of trials on *SI* ($p < 0.01$) with a medium effect size ($\omega^2 = 0.11$).

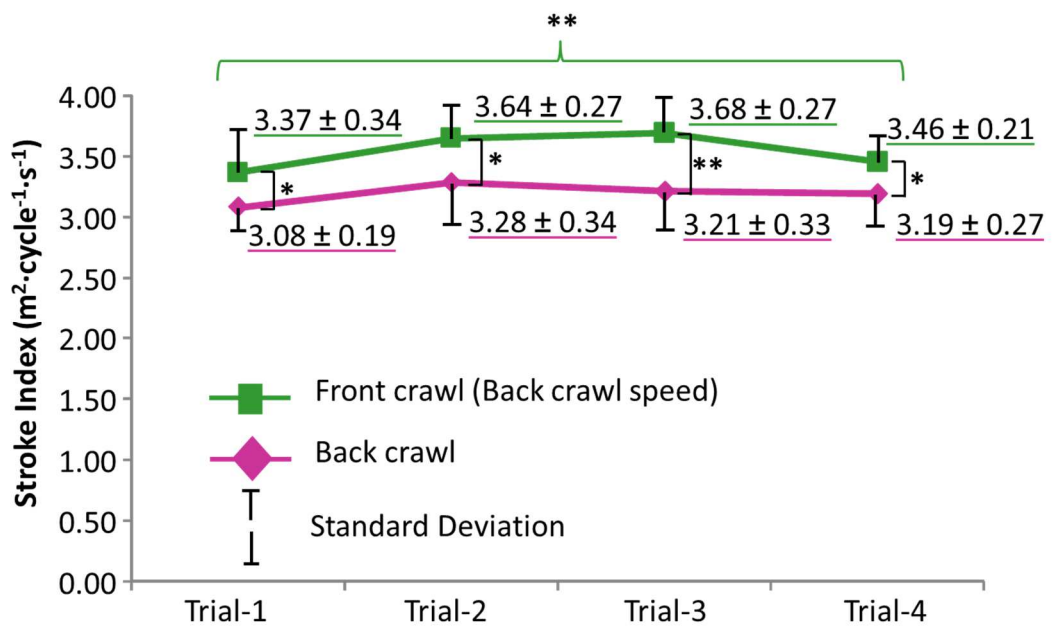


Figure 4. 30: Stroke index at four times 50-m trials in back crawl and front crawl at the same testing speeds. ** $p < 0.01$, * $p < 0.05$

4.3.2. Duration of the Phase

4.3.2.1. Duration of Each Phase

Figure 4.31 shows the duration of each phase (Entry, Pull, Push, Release, and Above-water) of the swimmers in all trials. In all trials, swimmers spent significantly longer duration in the release and above-water phases in BC than those in FC@BC ($p < 0.01$). On the other hand, the duration of the entry phase in FC@BC was significantly longer than that in BC ($p < 0.01$). The duration of the push phase in FC@BC was significantly longer than that in BC in trial-1, trial-2, and trial-3 ($p < 0.05$). Although there was no significant difference in the push phase between BC and FC@BC, the effect size was nearly large ($d = 0.74$).

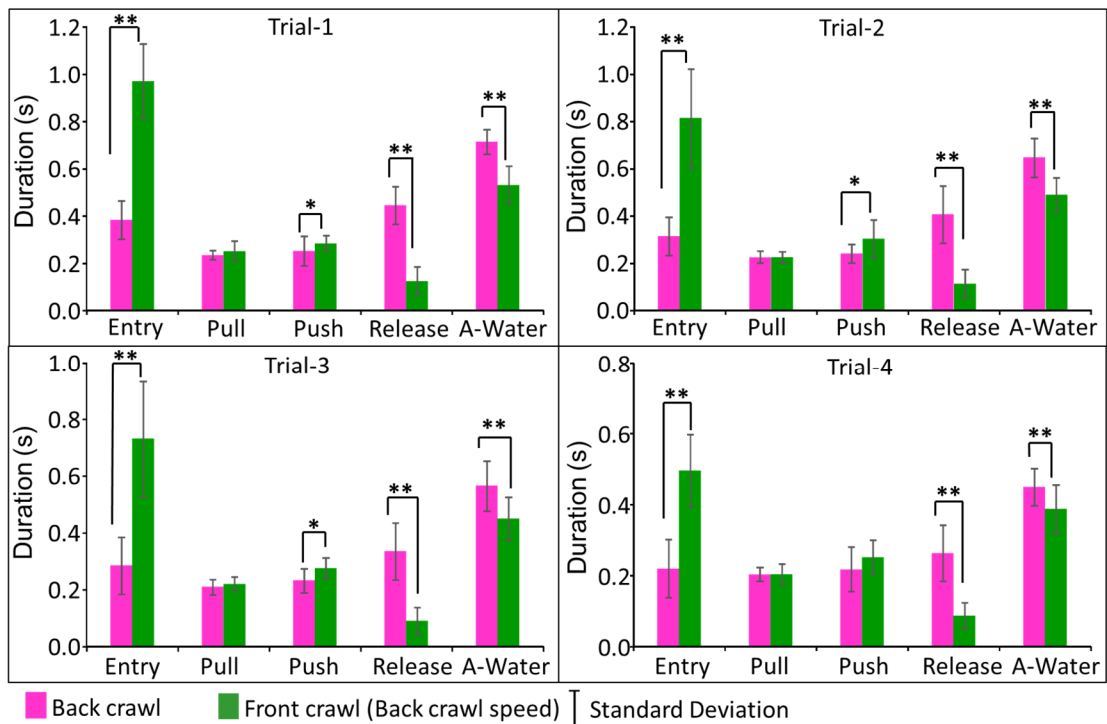


Figure 4. 31: Duration of each phase during the stroke cycle at four times 50m trials in back crawl and front crawl at the back crawl trial speeds. ** $p < 0.01$, * $p < 0.05$

Figure 4.32 shows the relationship between swimming speed (trials) and relative phase durations. There were significant main effects of the trial on relative duration phase in the pull ($p < 0.01$), push ($p < 0.05$), and above-water ($p < 0.01$) phase in BC, and the entry ($p < 0.01$), pull ($p < 0.01$), push ($p < 0.01$), and above-water ($p < 0.01$) phase in FC@BC. The effect sizes of these main effects are medium in the pull phase ($\omega^2 = 0.09$), medium in the push phase ($\omega^2 = 0.09$), and small-medium in the above-water phase ($\omega^2 = 0.04$) in BC and large in the entry phase ($\omega^2 = 0.34$), medium in the pull phase ($\omega^2 = 0.09$), and medium in the push ($\omega^2 = 0.09$), and medium in the above-water phase ($\omega^2 = 0.09$) in FC@BC.

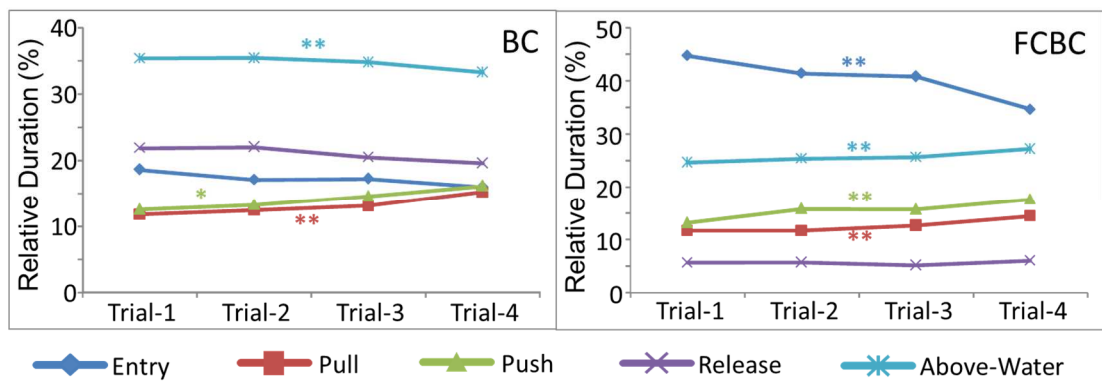


Figure 4. 32: Significant main effects of trials on the duration of each phase relative to the stroke cycle time in back crawl and front crawl at the back crawl trial speeds.
****p<0.01, *p<0.05**

4.3.2.2. Duration of Propulsive and Non-Propulsive Phases

Figure 4.33 shows the absolute duration of the propulsive phases (the pull and push phases). The duration of the propulsive phases in FC@BC was significantly longer than that in BC in trial-2, trial-3, and trial-4 ($p < 0.05$) with large and medium effect sizes (trial-2: $d = 1.30$, trial-3: $d = 0.50$, trial-4: $d = 0.66$). Although there was no significant difference in the propulsive phases duration between FC@BC and BC in trial-1, the propulsive phases duration value in FC@BC was longer than that in BC with a large effect size ($d = 0.80$).

Figure 4.34 shows the absolute duration of sum of the non-propulsive phases (the entry, release, and above-water phases). There were no differences between BC and FC@BC in sum of the non-propulsive phases.

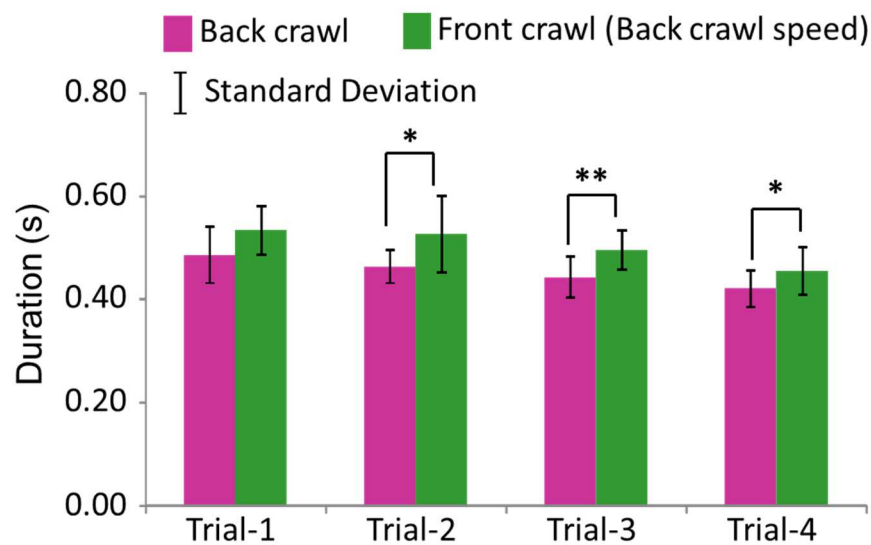


Figure 4. 33: The absolute duration of the propulsive phase during the stroke cycle at four times 50m trials in back crawl and front crawl at the back crawl trial speeds. ** $p < 0.01$. * $p < 0.05$

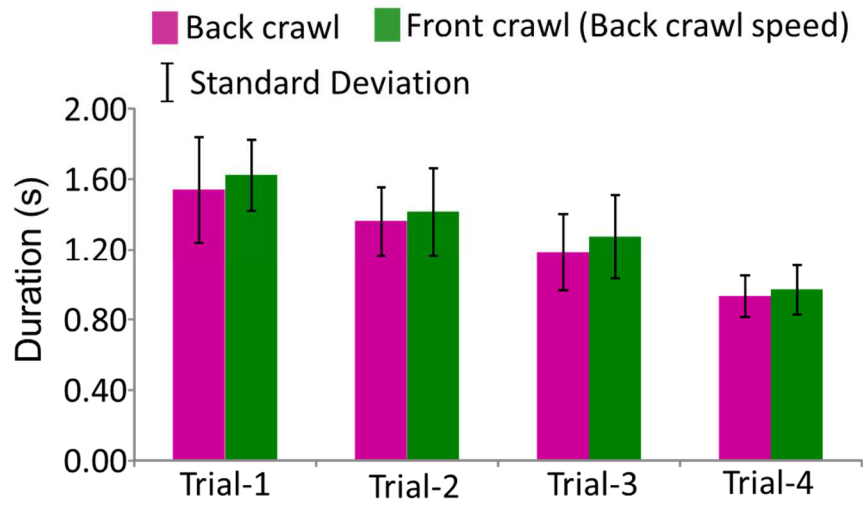


Figure 4. 34: The absolute duration of the non-propulsive phase during the stroke cycle at four times 50m trials in back crawl and front crawl at the back crawl trial speeds. **p<0.01. *p<0.05

4.3.3. Intra-Cycle Velocity in Swimming Direction

4.3.3.1. Intra-Cycle Velocity Variation in Swimming Direction

Figure 4.35 shows the intra-cycle velocity variation in swimming direction (IVV_x) in BC and FC@BC. In trial-3 and trial-4, IVV_x in BC was significantly larger than those in FC@BC. Although there was no significant difference in trial-2 between the strokes, IVV_x value in BC was larger than that in FC@BC with a medium effect size ($d=0.58$). In trial-1, there was no significant difference and the effect size was small ($d=0.38$).

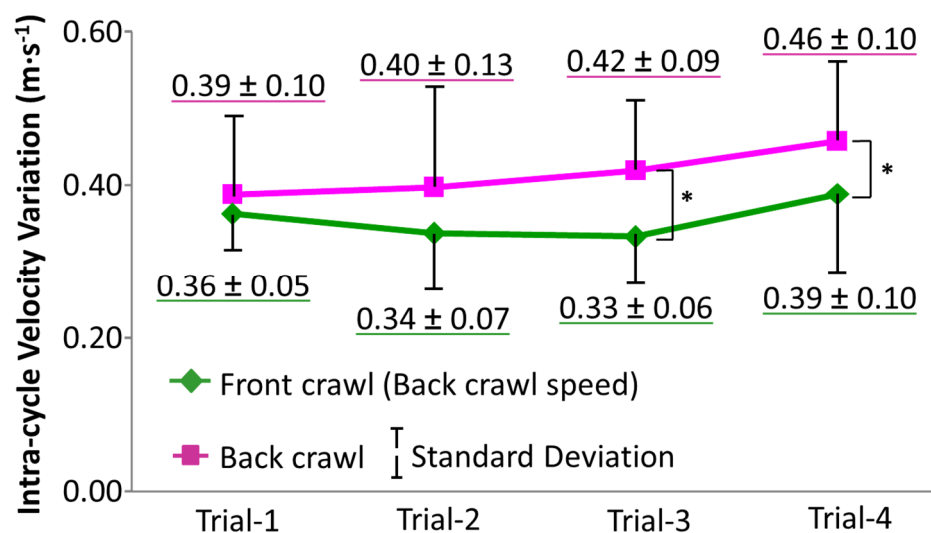


Figure 4. 35: Intra-cycle velocity variation during the stroke cycle at four times 50m trials in back crawl and front crawl at the same testing speeds. * $p<0.05$

4.3.3.2. Intra-Cycle Maximum Velocity

Figure 4.36 shows the intra-cycle maximum velocity (IV_{max}) in BC and FC@BC. There were no significant differences between the strokes in all trials, and the effect sizes were small (trial-1: $d=0.09$, trial-2: $d=0.39$, trial-3: $d=0.12$, trial-4: $d=0.37$). There was a significant main effect of the trial on IV_{max} in FC@BC with a large effect size ($p<0.01$, $\omega^2=0.59$).

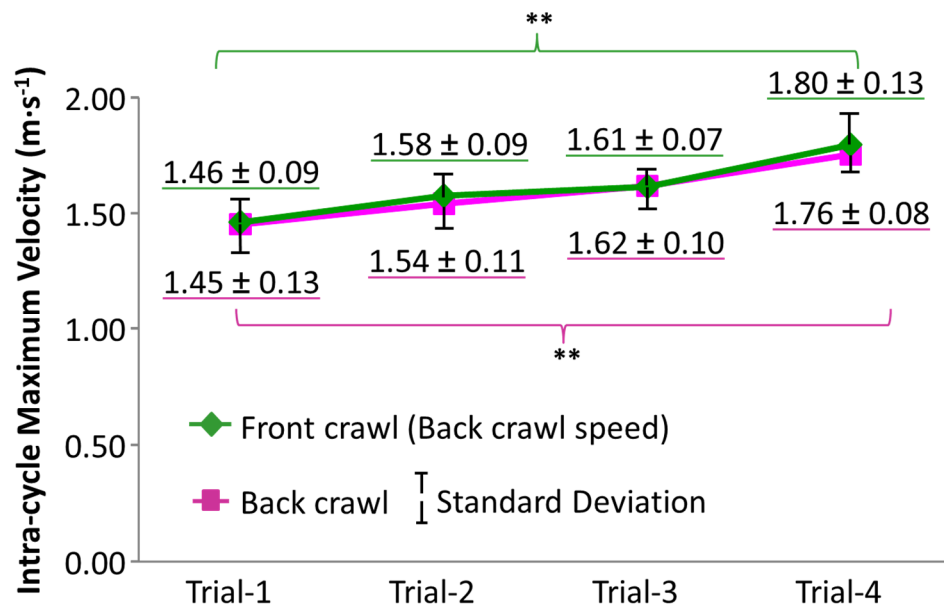


Figure 4. 36: Intra-cycle maximum velocity during the stroke cycle at four times 50m trials in back crawl and front crawl at the same testing speeds. ** $p<0.01$, * $p<0.05$

4.3.3.3. Intra-Cycle Minimum Velocity

Figure 4.37 shows the intra-cycle minimum velocity (IV_{min}) in BC and FC@BC. Swimmers had significantly faster IV_{min} in FC@BC than in BC in trial-2 ($p<0.05$), trial-3 ($p<0.01$), and trial-4 ($p<0.05$) with middle or large effect sizes (trial-2: $d=0.54$, trial-3: $d=0.80$, trial-4: $d=1.14$). In trial-1, the effect size of the difference was small ($d=0.33$) and not significant. There was a significant main effect of the trial on IV_{min} in FC@BC with a large effect size ($p<0.01$, $\omega^2=0.54$).

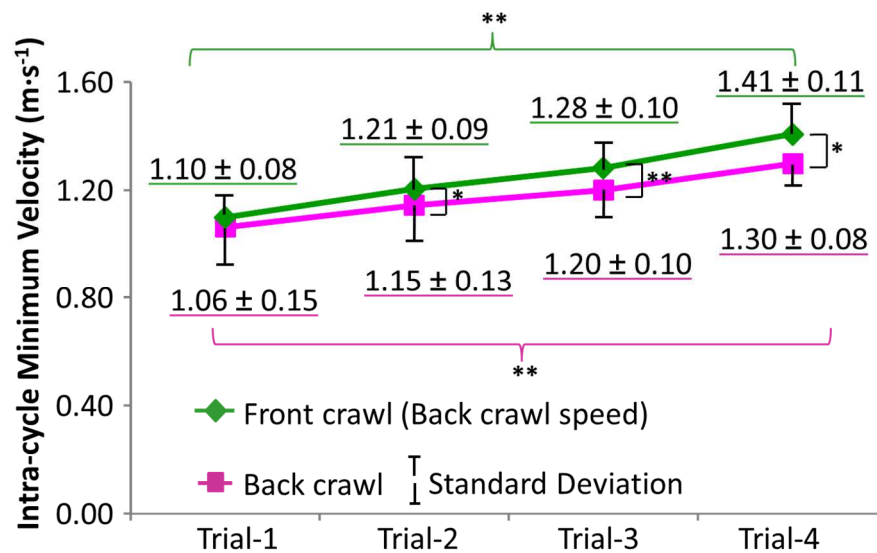


Figure 4. 37: Intra-cycle minimum velocity during the stroke cycle at four times 50m trials in back crawl and front crawl at the same testing speeds. ** $p<0.01$, * $p<0.05$

4.3.4. The Maximum Distance between the Hand and COM in Lateral Direction

Figure 4.38 shows the maximum distance between the hand and COM in lateral-direction under the water in BC and FC@BC. In all trials, swimmers had larger maximum distance between the hand and COM in BC than in FC@BC ($p < 0.01$) with large effect sizes (trial-1: $d = 2.93$, trial-2: $d = 2.97$, trial-3: $d = 3.37$, trial-4: $d = 2.66$). There were no main effect of the trial on the maximum distance in FC@BC.

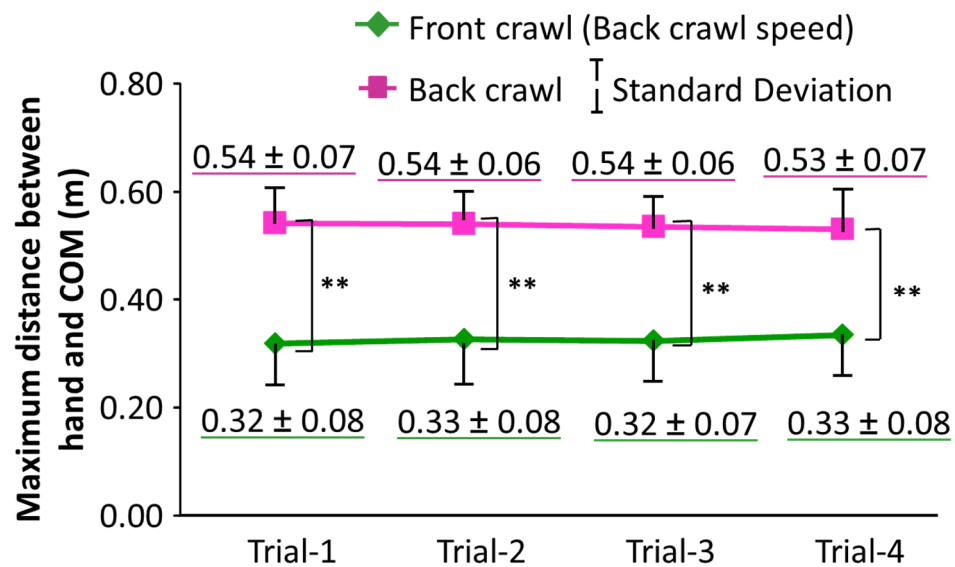


Figure 4. 38: Underwater maximum distance between the hand and the centre of mass during the stroke cycle at four times 50m trials in back crawl and front crawl at the same testing speeds. ** $p < 0.01$

4.3.5. Yaw Angle Fluctuation

Figure 4.39 shows the yaw angle fluctuation in BC and FC@BC. Swimmers had significantly larger yaw angle fluctuation in BC than in FC@BC with a large effect size at trial-1 ($p < 0.05$, $d = 1.13$). Although there were no significant differences in the yaw angle fluctuation between the strokes at trial-2, trial-3, trial-4, the yaw angle fluctuation values in BC in these trials were larger than those in FC@BC with effect sizes ranging from medium to large (trial-2: $d = 0.56$, trial-3: $d = 0.80$, trial-4: $d = 0.68$). There were no main effect of the trial on the yaw angle fluctuation in FC@BC.

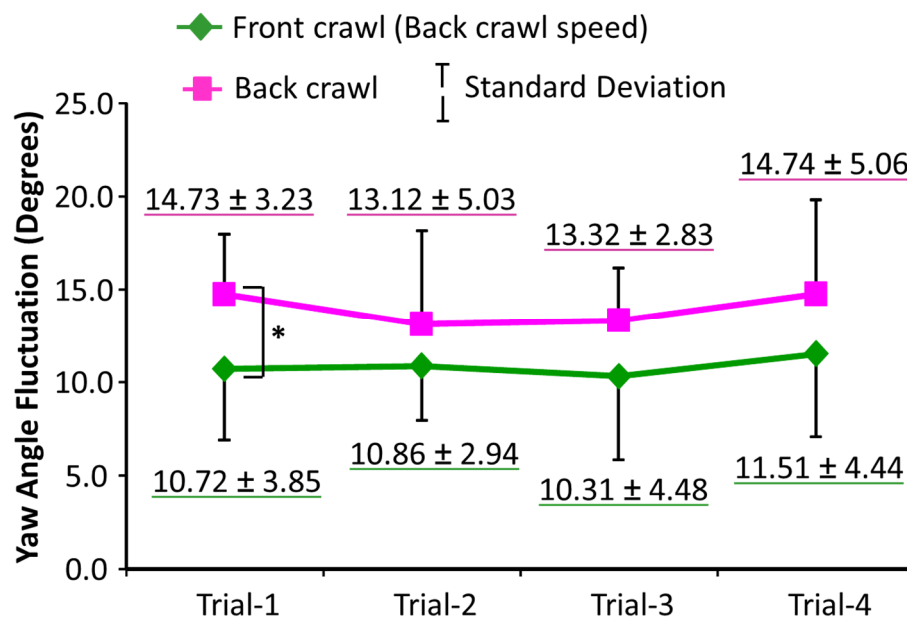


Figure 4. 39: The yaw angle fluctuation during the stroke cycle at four times 50m trials in back crawl and front crawl at the same testing speeds. ** $p < 0.01$, * $p < 0.05$

4.3.6. Shoulder and Hip Roll Angle

4.3.6.1. Maximum Shoulder Roll Angle

Figure 4.40 shows maximum shoulder roll angle of swimmers in BC and FC@BC.

Swimmers had larger shoulder maximum roll angle in FC@BC than in BC at all trials with large effect sizes (trial-1: $p<0.01$, $d=2.22$, trial-2: $p<0.01$, $d=1.75$, trial-3: $p<0.05$, $d=1.13$, trial-4: $p<0.01$, $d=1.29$).

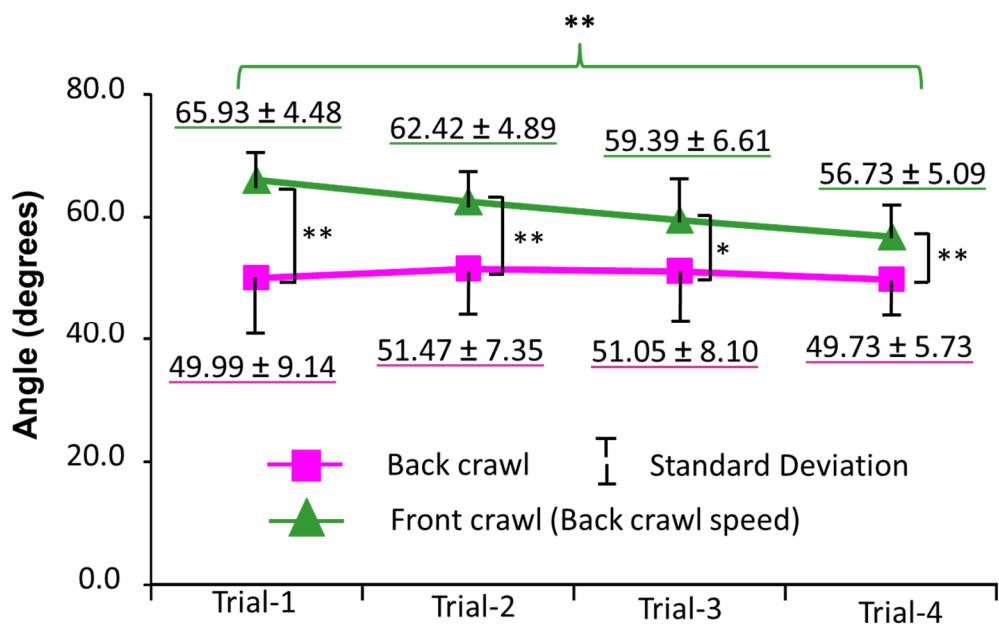


Figure 4. 40: Maximum shoulder roll angle during the stroke cycle at four times 50m trials in back crawl and front crawl at the same testing speeds. ** $p<0.01$, * $p<0.05$

4.3.6.2. Maximum Hip Roll Angle

Figure 4.41 shows maximum hip roll angle of swimmers in BC and FC@BC. Swimmers had larger maximum hip roll angle with large effect sizes in trial-1 ($p < 0.01$, $d = 2.35$), trial-2 ($p < 0.01$, $d = 1.67$), and trial-3 ($p < 0.05$, $d = 1.00$). There was no difference in maximum hip roll angle in trial 4 and the effect size was small-medium ($d = 0.36$). There was a significant main effect of trials on maximum roll angle in FC@BC with a large effect size ($p < 0.01$, $\omega^2 = 0.38$).

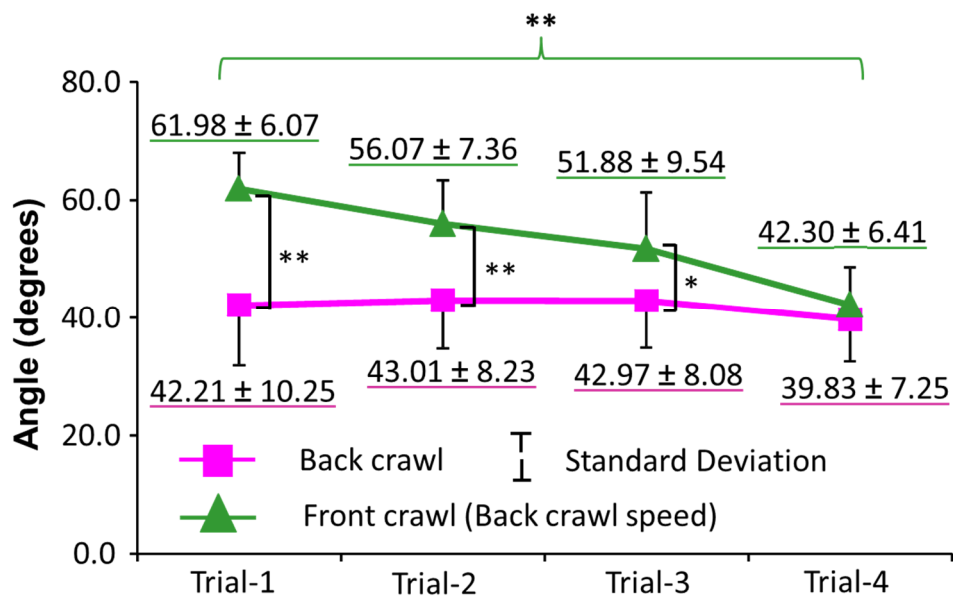


Figure 4. 41: Maximum hip roll angle during the stroke cycle at four times 50m trials in back crawl and front crawl at the same testing speeds. ** $p < 0.01$, * $p < 0.05$

4.3.7. Hand Speed and Accerelation

4.3.7.1. Mean Hand Speed in the Swimming Direction During the Pull Phase

Figure 4.42 shows the mean hand speed in swimming (x) direction during the pull phase in BC and in FC@BC. There were no significant differences in the mean hand speed between the strokes, and there were no main effects of the trial on the mean hand speed in BC and FC@BC.

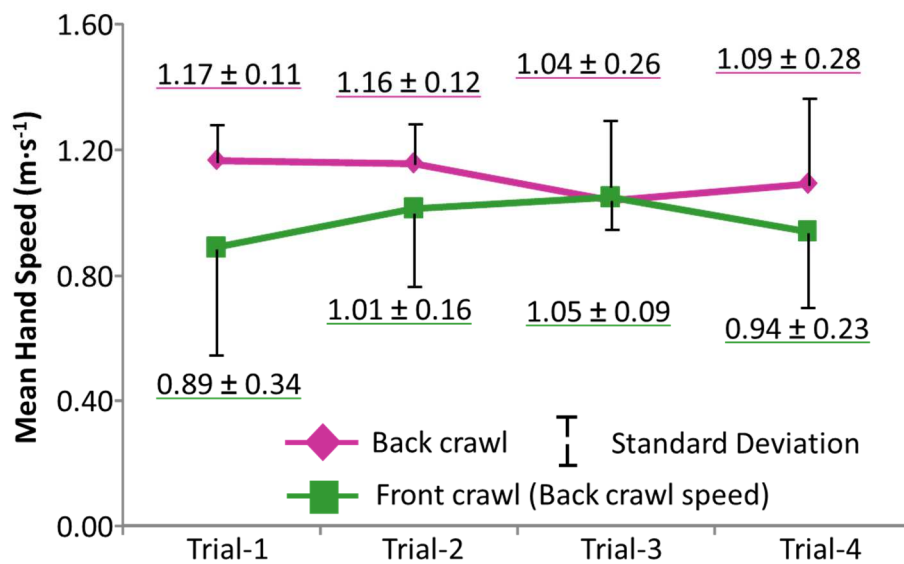


Figure 4. 42: Mean hand speed in the swimming direction during the pull phase at four times 50m trials in front crawl and back crawl at the same testing speeds.

4.3.7.2. Mean Hand Speed in the Swimming Direction During the Push Phase

Figure 4.43 shows the mean hand speed in swimming direction during the push phase in BC and FC@BC. The mean hand speed in swimming (x) direction in BC was significantly larger than that in FC@BC at each trial (trial-1: $p < 0.05$, trial-2: $p < 0.05$, trial-3: $p < 0.01$, trial-4: $p < 0.05$). The effect size of these differences were large (trial-1: $d = 1.18$, trial-2: $d = 0.95$, trial-3: $d = 1.23$, trial-4: $d = 0.81$). There were no main effects of the trial on the hand speed during the push phase in both BC and FC@BC.

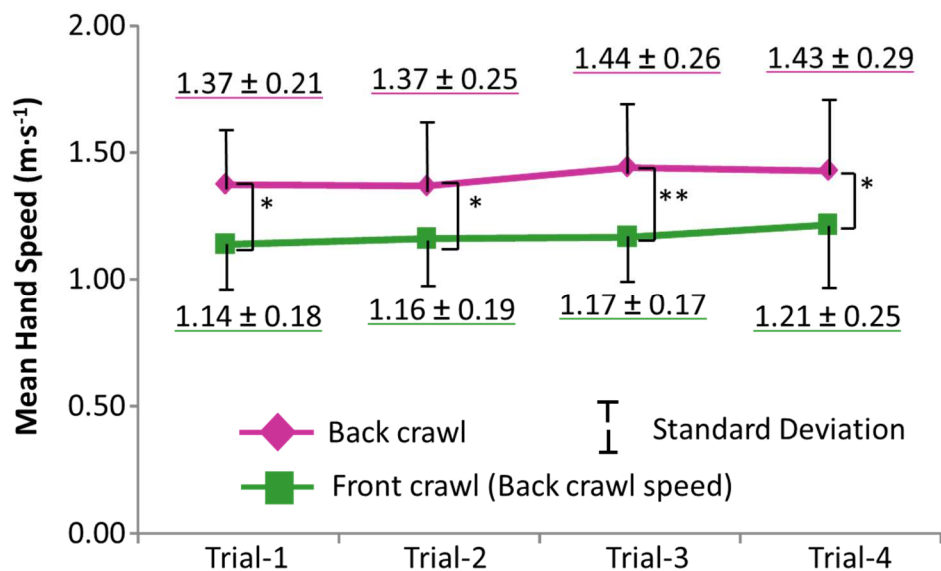


Figure 4. 43: Mean hand speed in the swimming direction during the push phase at four times 50m trials in front crawl and back crawl at the same testing speeds. * $p < 0.05$, ** $p < 0.01$

4.3.7.3. Mean Hand Acceleration during the Pull Phase

Figure 4.44 shows the mean hand acceleration in swimming (x) direction during the pull phase in FC@BC and BC. The mean hand acceleration in swimming direction during the pull phase in BC was significantly larger than that in FC@BC at all trials ($p < 0.01$) with large effect sizes (trial-1: $d = 1.45$, trial-2: $d = 1.64$, trial-3: $d = 1.29$, trial-4: $d = 1.80$). There was also a significant main effect of trials on mean hand acceleration during the push phase in FC@BC ($p < 0.01$) with a medium effect size ($\omega^2 = 0.10$).

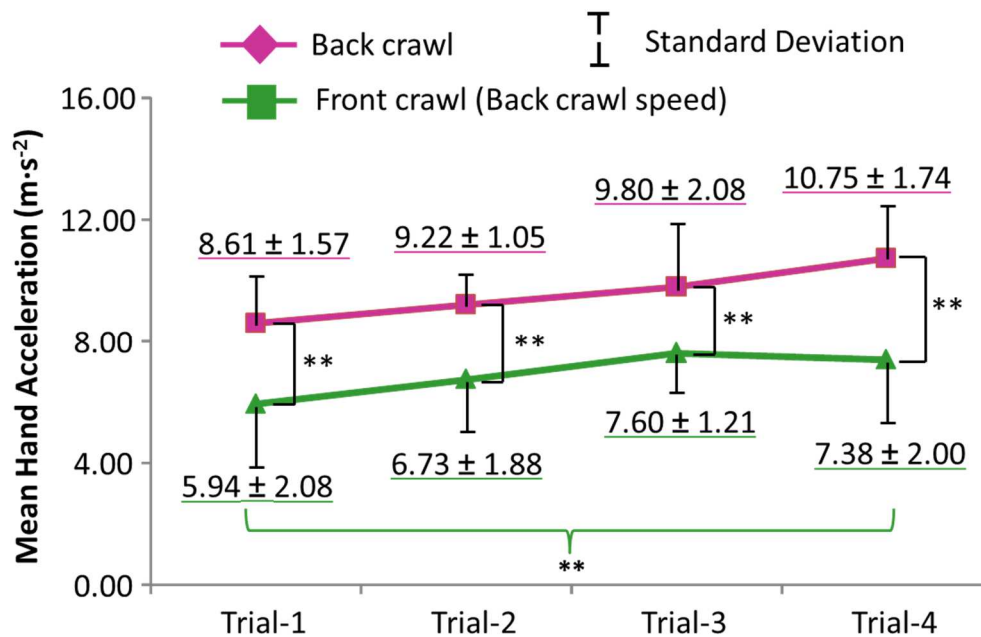


Figure 4. 44: Mean hand acceleration in the swimming direction during the pull phase at four times 50m trials in front crawl and back crawl at the same testing speeds. * $p < 0.05$, ** $p < 0.01$

4.3.7.4. Mean Hand Acceleration during the Push Phase

Figure 4.45 shows the mean hand acceleration in swimming (x) direction during the push phase in FC@BC and BC. The mean hand deceleration in swimming direction during the push phase in FC@BC than in BC at all trials ($p < 0.01$) with large effect sizes (trial-1: $d = 2.72$, trial-2: $d = 3.01$, trial-3: $d = 1.75$, trial-4: $d = 2.07$). There was also significant main effect of trials on mean hand acceleration during the push phase in FC@BC ($p < 0.01$) with a large effect size ($\omega^2 = 0.36$).

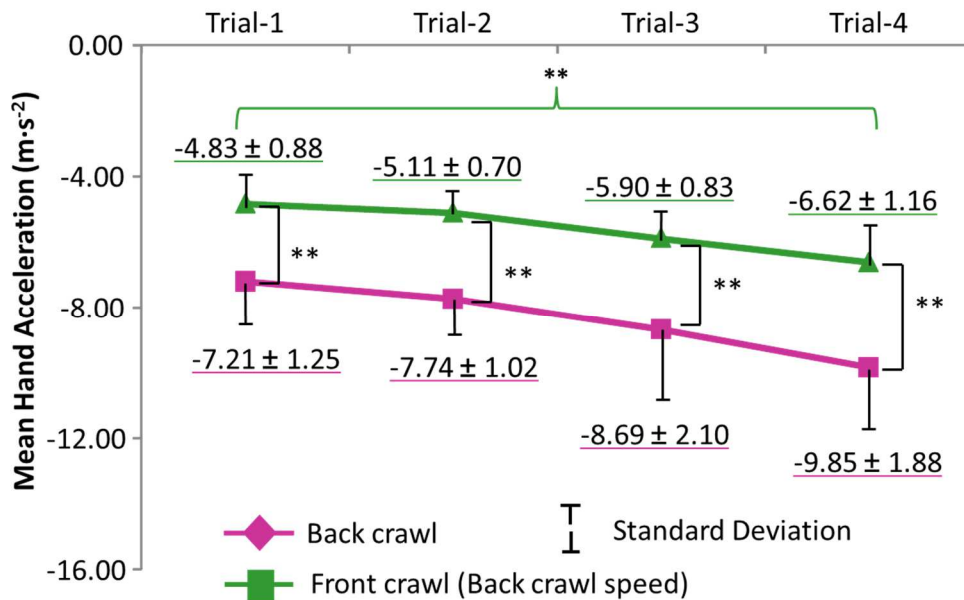


Figure 4. 45: Mean hand acceleration in the swimming direction during the push phase at four times 50m trials in front crawl and back crawl at the same testing speeds. ** $p < 0.01$

4.3.7.5. Mean Hand Speed during the Underwater Phases in the Vertical Direction

Figure 4.46 shows the mean hand speed during the underwater phases in the vertical (y) direction in BC and FC@BC. There were significant main effects of the trial on the mean hand speed in the vertical direction in both BC ($p < 0.01$, $\omega^2 = 0.64$) and FC@BC ($p < 0.01$, $\omega^2 = 0.72$). There were no significant differences in the mean hand speed in the vertical direction between BC and FC@BC at any trials.

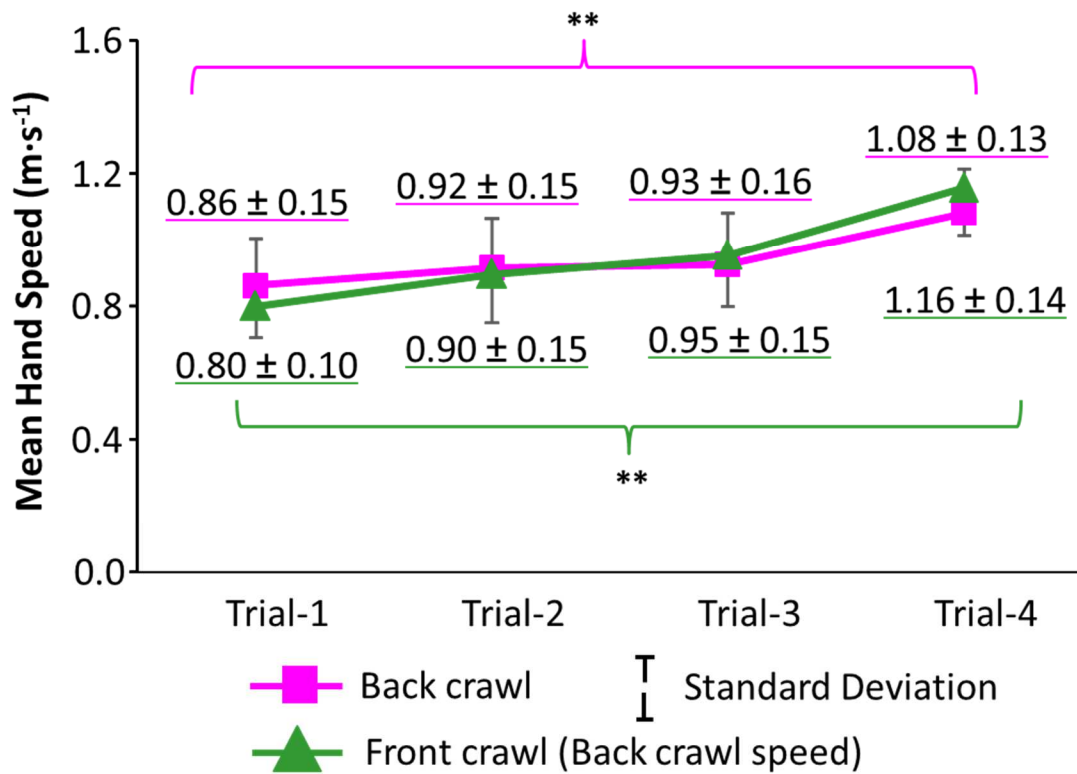


Figure 4. 46: Mean hand speed during the underwater phases in the vertical direction at four times 50m trials in front crawl and back crawl at the same testing speeds. ** $p < 0.01$

4.3.7.6. Mean Hand Speed during the Underwater Phases in the Lateral Direction

Figure 4.47 shows the mean hand speed during the underwater phases in the lateral (z) direction in BC and FC@BC. There were significant main effects of the trial on the mean hand speed in the lateral direction in both BC ($p < 0.01$, $\omega^2 = 0.97$) and FC@BC ($p < 0.01$, $\omega^2 = 0.45$). There were significant differences in the mean hand speed in the lateral direction between BC and FC@BC at all trials with large effect sizes (trial-1: $p < 0.01$, $d = 5.55$, trial-2: $p < 0.01$, $d = 3.91$, trial-3: $p < 0.01$, $d = 4.06$, trial-4: $p < 0.01$, $d = 4.44$).

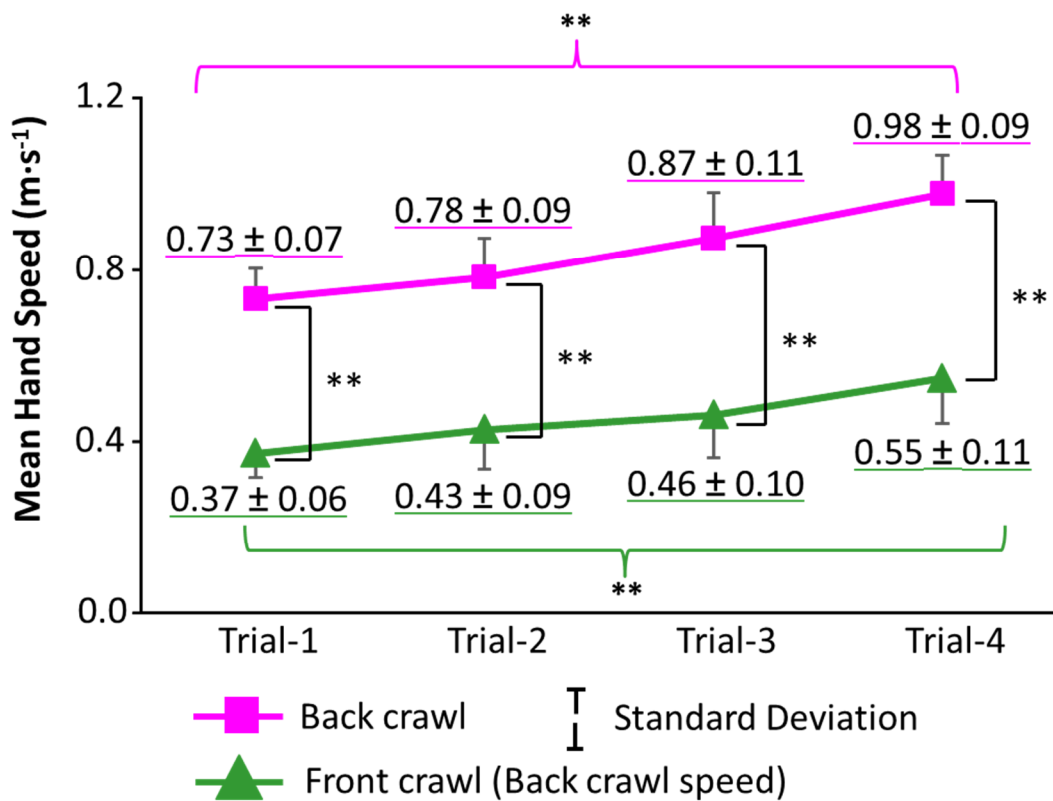


Figure 4. 47: Mean hand speed during the underwater phases in the lateral direction at four times 50m trials in front crawl and back crawl at the same testing speeds. **p<0.01

4.3.7.7. Mean 3D Hand Speed Relative to COM

Figure 4.48 shows the mean 3D hand speed during the stroke cycle in BC and FC@BC. The mean 3D hand speed during the stroke cycle in BC was significantly larger than that in FC@BC at all trials ($p < 0.01$) with large effect sizes (trial-1: $d = 1.57$, trial-2: $d = 1.43$, trial-3: $d = 1.59$, trial-4: $d = 2.00$). There were significant main effects of the trial on the 3D hand speed in FC@BC with a large effect size ($p < 0.01$, $\omega^2 = 0.55$).

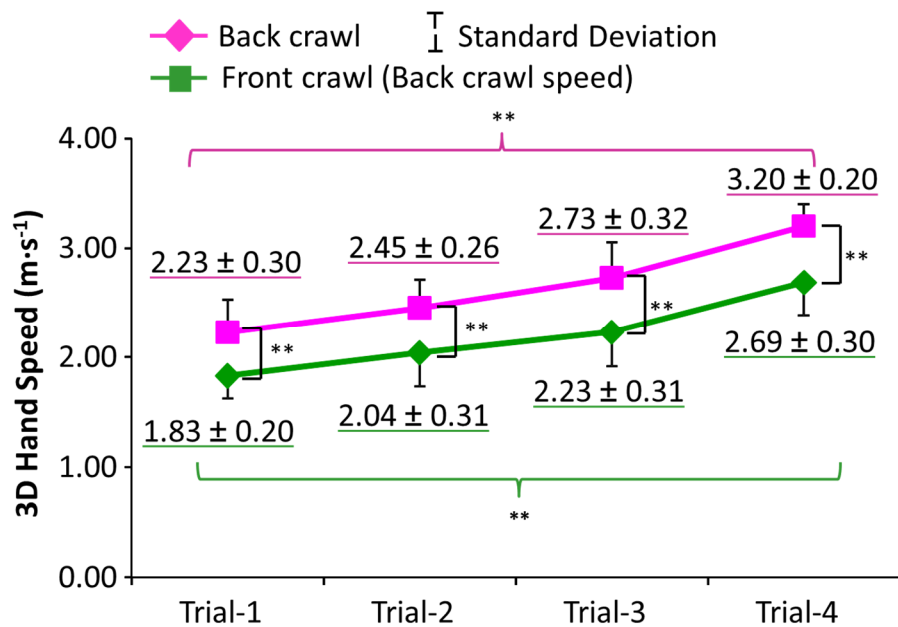


Figure 4. 48: The mean 3D hand speed relative to COM during the stroke cycle at four times 50m trials in back crawl and front crawl at the same testing speeds. ****p<0.01**

4.3.7.8. The Mean 3D Hand Speed Relative to COM during Each Phase

Figure 4.49 shows the mean 3D hand speed during each stroke phase. During the release phase, swimmers had significantly faster 3D hand speed in in FC@BC than in BC at trial-1, trial-2, and trial-3 (all $p < 0.01$, $d > 0.8$). Swimmers had significantly faster 3D hand speed in BC than in FC@BC during the pull phase at every trial except at trial-1 (all $p < 0.01$ $d > 0.79$). During the above-water phase, swimmers had faster 3D hand speed in in BC than in FC@BC at trial-4 ($p < 0.05$), but the effect size was small ($d = 0.34$). During the entry phase, swimmers also had significantly faster 3D hand speed in BC than in FC@BC at every trial ($p < 0.01$, $d > 2.17$).

Although there wasn't a significant difference in the 3D hand speed between BC and FC@BC during the pull phase at trial-1, the mean 3D hand speed value was larger in BC than in FC@BC with medium effect size ($d = 0.62$). Also, swimmers had larger 3D hand speed value in FC@BC than in BC at trial-4 with a large effect size ($d = 1.13$), although the difference was not significant ($p = 0.06$).

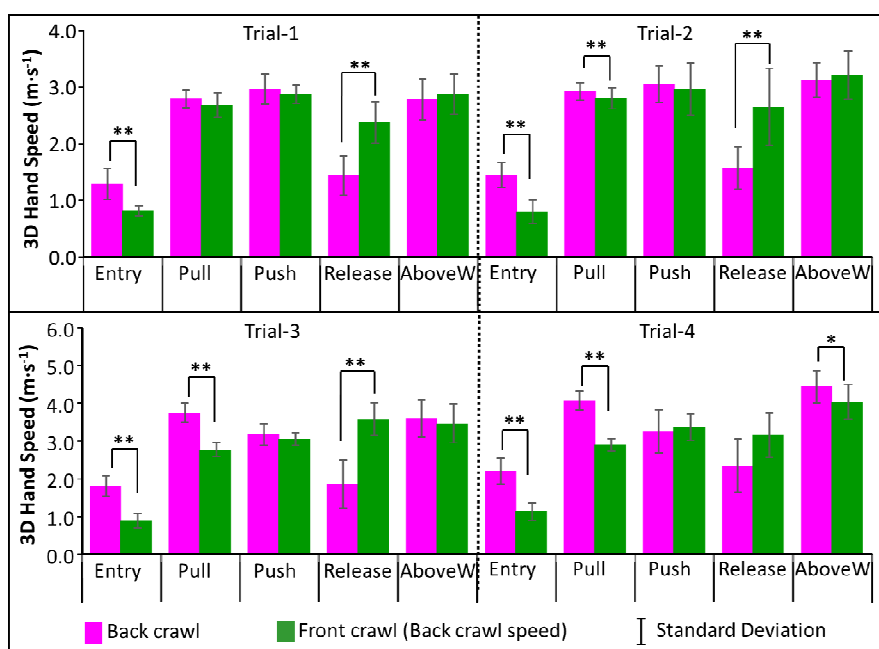


Figure 4. 49: The mean 3D hand speed relative to COM during each phase at four times 50m trials in back crawl and front crawl at the same testing speeds. * $p < 0.05$, ** $p < 0.01$

4.3.7.9. Mathematical Contribution of Each Phase on the Difference in the 3D Hand Speed

Figure 4.50 shows the differences in the product of the mean $3Du_{SC}$ in each phase and the relative duration of the phase (Contribution factor: $\frac{3Du_{Phase} \cdot d_{Phase}}{d_{SC}}$). There were significant differences in the contribution factor between BC and FC@BC during the all phases except during the pull phase at trial-1, trial-2, and trial-3. The phases which had larger contribution factors in BC than in FC@BC (i.e. the phases which positively contributed to the faster $3Du_{SC}$ in BC) were the pull, release, and above-water phases.

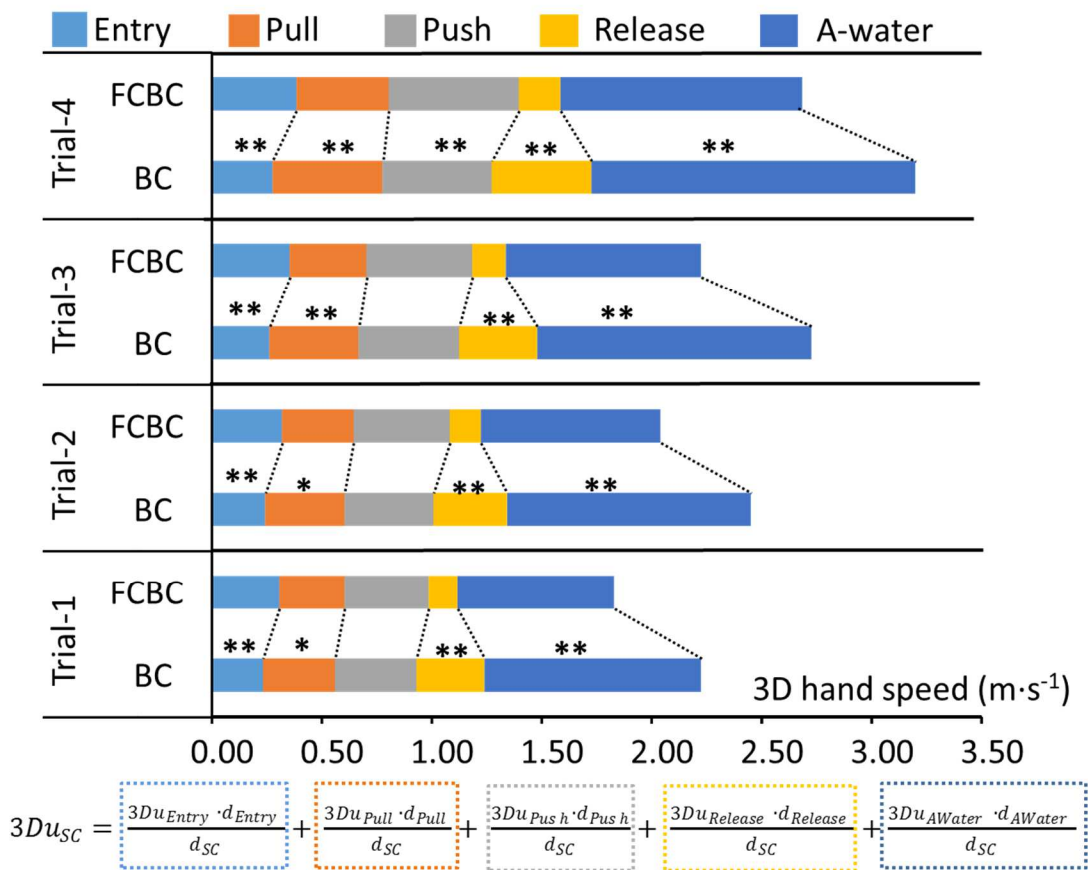


Figure 4. 50: Differences in the contribution factors of each phase between back crawl and front crawl at four times 50m trials in back crawl and front crawl at the same testing speeds. In the equation, d is the duration, SC is Stroke Cycle, $3Du$ is the 3D hand speed. ** $p < 0.01$, * $p < 0.05$

4.3.8. Froude Efficiency

Figure 4.51 shows η_F in FC@BC and BC. η_F in FC@BC was higher than that in BC at every trial with larger effect sizes (trial-1: $p<0.01$, $d=3.45$, trial-2: $p<0.01$, $d=2.28$, trial-3: $p<0.01$, $d=2.95$, trial-4: $p<0.01$, $d=2.67$). There was a significant main effect of the trial on η_F in FC@BC ($p<0.01$) with a large effect size ($\omega^2=0.37$).

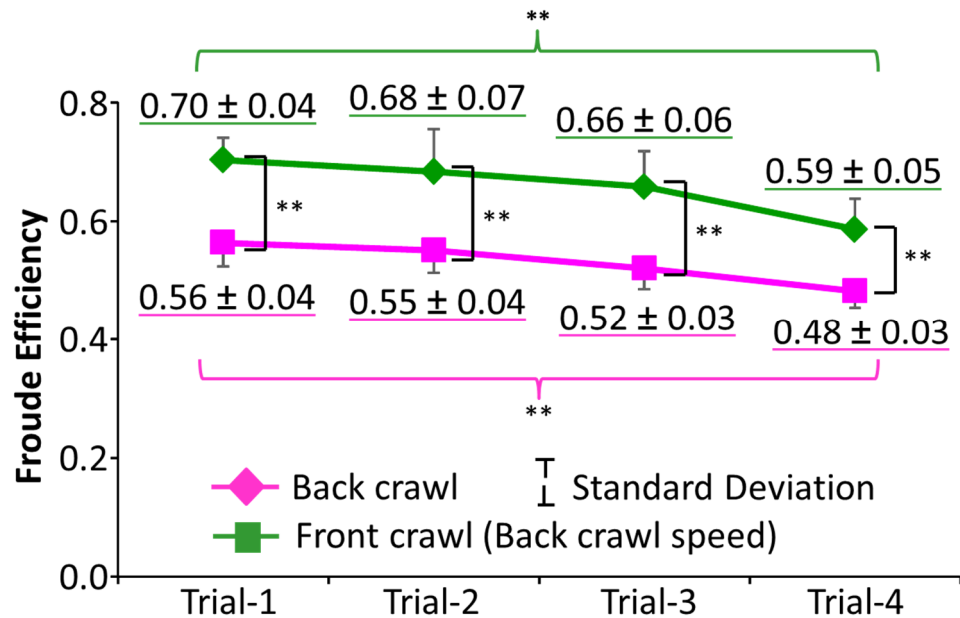


Figure 4. 51: Froude efficiency during the stroke cycle at four times 50m trials in back crawl and front crawl at the back crawl trial speeds. ** $p<0.01$

4.3.9. 3D Hand Path Distance

4.3.9.1. 3D Hand Path Distance during the Underwater Phase

Figure 4.52 shows the distance of the 3D hand path in BC and FC@BC speeds. Swimmers had significantly longer hand path distance in BC than in FC@BC at trial-2 ($p < 0.05$, $d = 0.93$). Although there were no significant differences in the 3D hand path at trial-1 and trial-4, the effect sizes were middle (trial-1: $d = 0.52$, trial-4: $d = 0.67$). There was no significant difference in the 3D hand path distance at trial-3 and the size of the effect was small ($d = 0.35$). There was a significant main effect of the trial on the 3D hand path distance in FC@BC ($p < 0.01$, $\omega^2 = 0.18$).

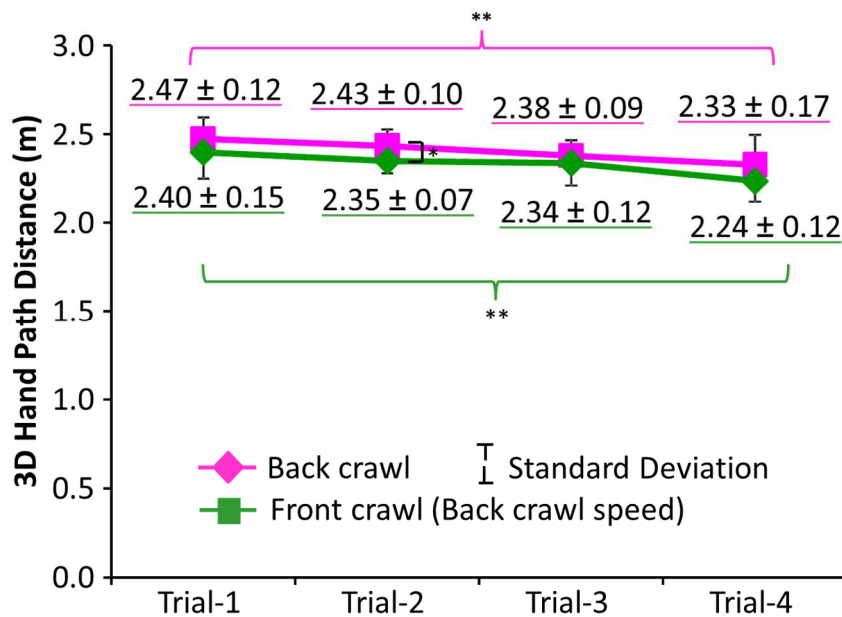


Figure 4. 52: Underwater 3D hand path distance during the stroke cycle at four times 50m trials in back crawl and front crawl at the same testing speeds. ** $p < 0.01$, * $p < 0.05$

4.3.9.2. 3D Hand Path Distance during Each Phase

Figure 4.53 shows the distance of 3D hand path in each trial. 3D hand path in BC was significantly longer than that in FC@BC during the release and above-water phases in all trials with large effect sizes ($d > 2.73$). The 3D hand path distance in BC was significantly shorter than that in FC@BC during the entry phase at all trials with large effect sizes ($d > 1.86$). Swimmers had shorter 3D hand path distance in BC than that in FC@BC during the push phase at trial-2, trial-3, and trial-4 with large effect sizes (trial-2: $d = 2.45$, trial-3: $d = 1.56$, trial-4: $d = 2.55$).

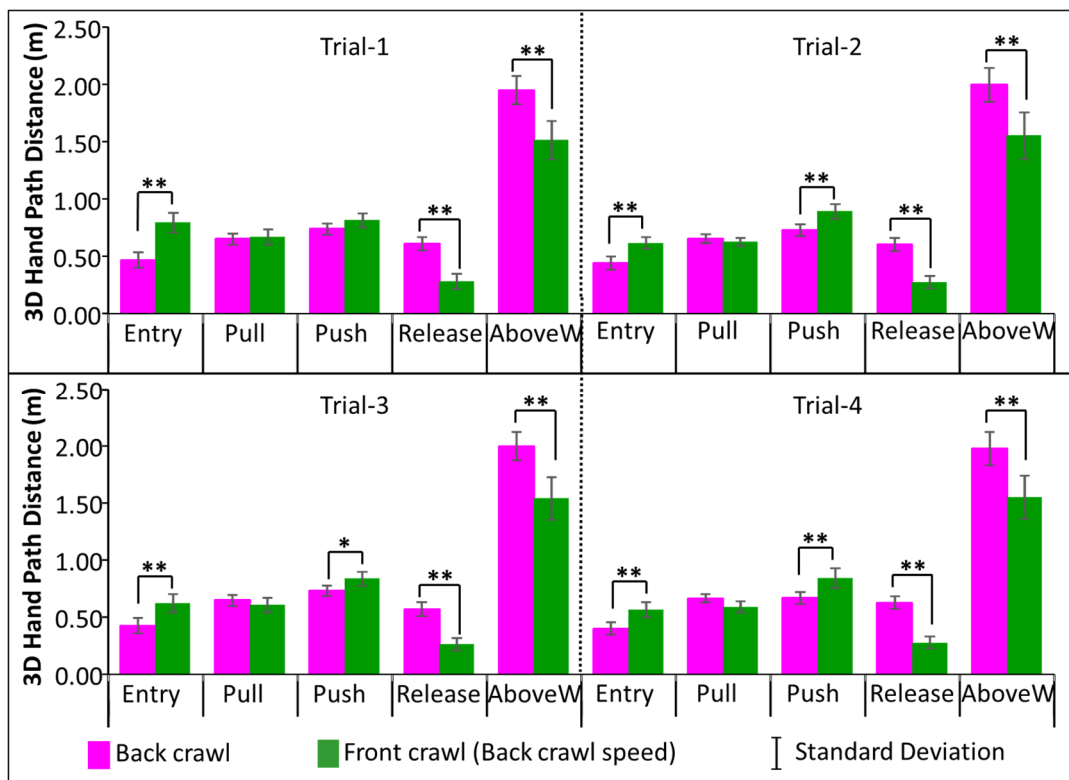


Figure 4. 53: 3D hand path distance during each phase at four times 50m trials in back crawl and front crawl at the same testing speeds. ** $p < 0.01$, * $p < 0.05$

4.3.10. The Vertical Displacement of COM

4.3.10.1. The Mean Vertical Displacement of COM

Figure 4.54 shows the mean COM displacement in vertical-direction during the stroke cycle in BC and FC@BC. The mean COM displacement in vertical-direction in FC@BC was larger than that in BC (the COM displacement in BC was deeper than that in FC@BC in the water in relation to the water surface) at all trials ($p<0.01$) with effect sizes ranging from medium to large (trial-1: $d=0.50$, trial-2: $d=1.00$, trial-3: $d=0.50$, trial-4: $d=1.27$). There was also a significant main effect of the trial on the mean COM displacement in FC@BC ($p<0.01$) with a large effect size ($\omega^2=0.05$).

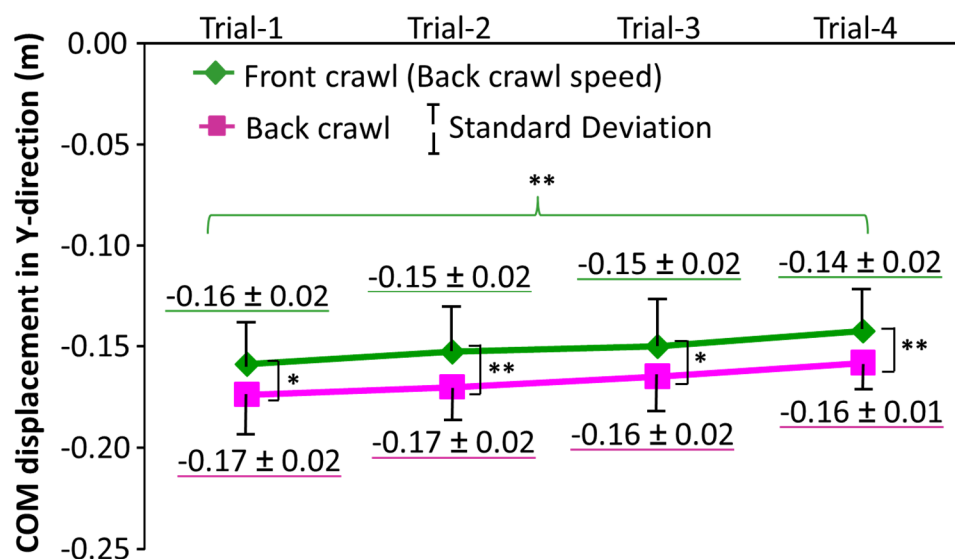


Figure 4. 54: The mean centre of mass displacement in vertical-direction during the stroke cycle at four times 50m trials in back crawl and front crawl at the same testing speeds. ** $p<0.01$

4.3.10.2. The Maximum Vertical Displacement of COM

Figure 4.55 shows the maximum COM displacement in vertical (y) direction during the stroke cycle in BC and FC@BC. The maximum COM displacement in vertical-direction in FC@BC was larger than that in BC (The maximum COM displacement was deeper in BC than in FC@BC) at all trials ($p < 0.01$ with effect sizes (trial-1: $d = 1.90$, trial-2: $d = 1.26$, trial-3: $d = 1.50$, trial-4: $d = 1.90$). There was also a significant main effect of the trial on the maximum COM displacement in FC@BC ($p < 0.01$) with a medium effect size ($\omega^2 = 0.07$).

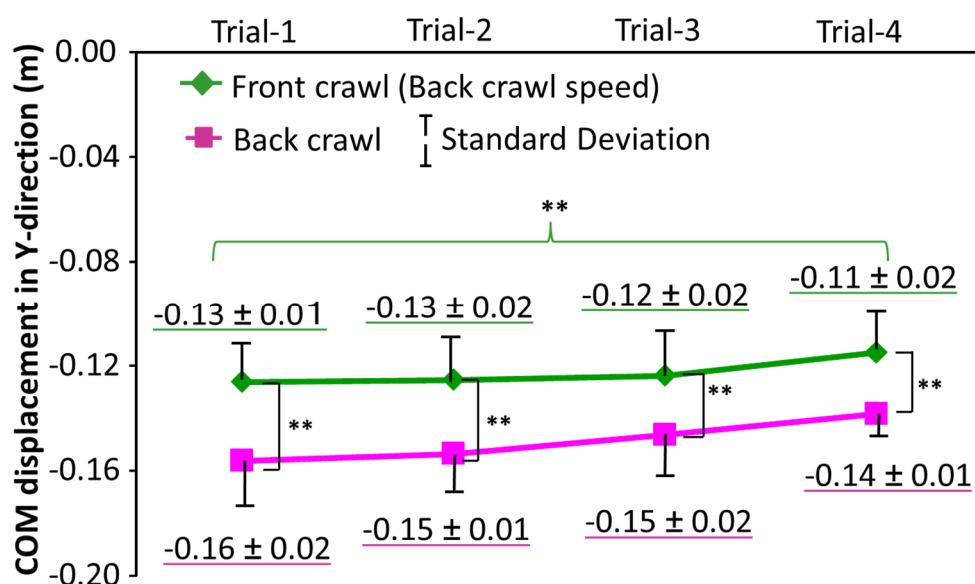


Figure 4. 55: Maximum centre of mass displacement in vertical-direction during the stroke cycle at four times 50m trials in back crawl and front crawl at the same testing speeds. ** $p < 0.01$

4.3.10.3. The Minimum Vertical Displacement of COM

Figure 4.56 shows the minimum COM displacement in vertical (y) direction during the stroke cycle in BC and FC@BC. There were no significant differences in the minimum COM displacement between FC@BC and BC at all trials, and effect sizes were small (trial-1: $d=0.39$, trial-2: $d<0.10$, trial-3: $d=0.39$, trial-4: $d<0.10$). There was also a significant main effect of the trial on the minimum COM displacement in FC@BC ($p<0.01$) with a small-medium effect size ($\omega^2=0.04$).

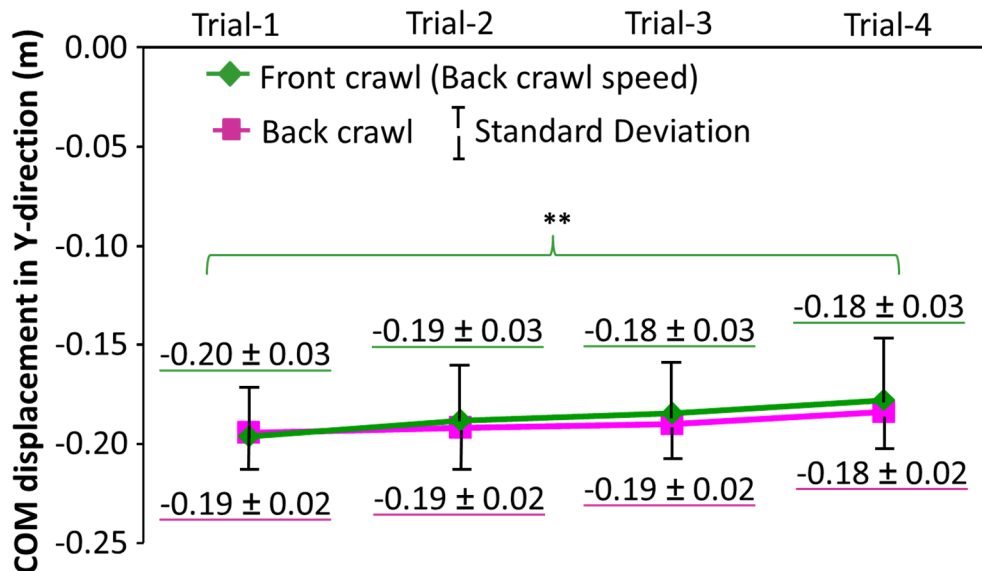


Figure 4. 56: Minimum centre of mass displacement in vertical-direction during the stroke cycle at four times 50m trials in front crawl and back crawl. **** $p<0.01$**

4.3.11. Vertical Displacement of the Foot

4.3.11.1. Mean Vertical Displacement of the Foot

Figure 4.57 shows the mean foot displacement in vertical (y) direction during the stroke cycle in BC and FC@BC. In FC@BC, the mean foot displacement values was negative, and the mean foot displacement in FC@BC was significantly larger (closer to the water surface) than that in BC ($p<0.01$) with large effect sizes (trial-1: $d=2.83$, trial-2: $d=3.33$, trial-3: $d=2.83$, trial-4: $d=3.11$). There was a significant main effect of the trial on the mean foot displacement in FC@BC ($p<0.01$) with a medium-large effect size ($\omega^2=0.11$).

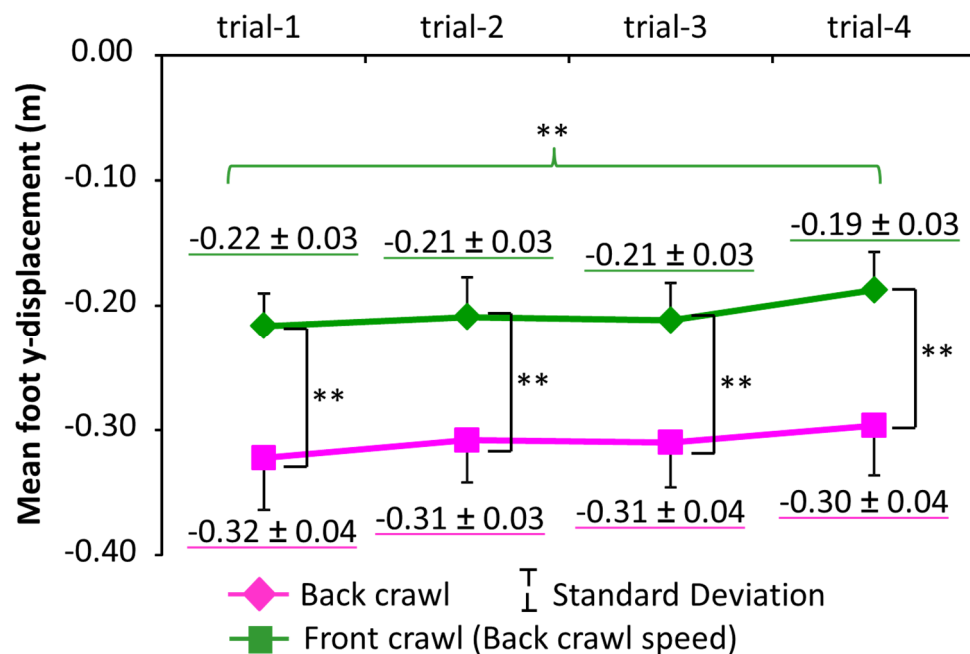


Figure 4. 57: Mean vertical displacement of the foot at four times 50m trials in back crawl and front crawl at the same testing speeds. **** $p<0.01$**

4.3.11.2. Minimum Vertical Displacement of the Foot

Figure 4.58 shows the minimum vertical (y) foot displacement during the stroke cycle in BC and FC@BC. In both BC and FC@BC, the minimum foot displacement values were negative (under the water). The minimum vertical displacement of the foot in BC was significantly lower than that in BC with large effect sizes (trial-1: $p < 0.01$, $d = 2.17$, trial-2: $p < 0.01$, $d = 2.00$, trial-3: $p < 0.01$, $d = 1.77$, trial-4: $p < 0.05$, $d = 0.99$). There were no significant main effects of the trial on the minimum vertical displacement in both BC and FC@BC.

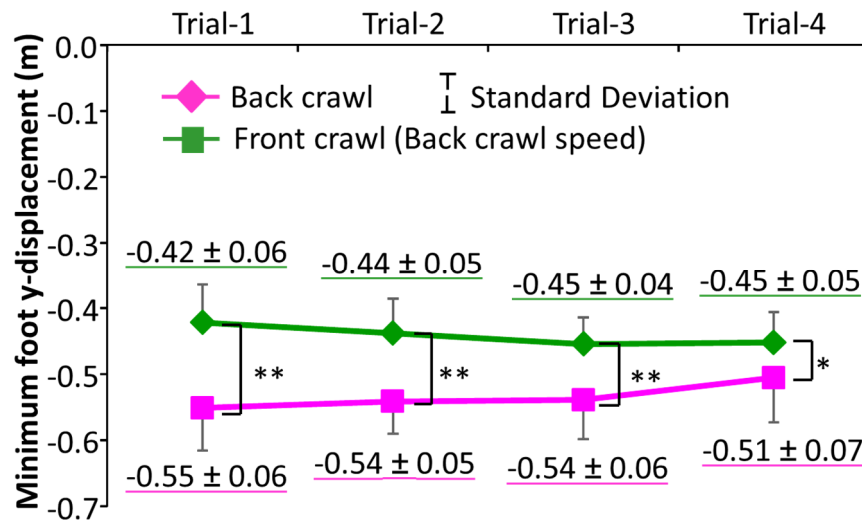


Figure 4. 58: Minimum vertical displacement of the foot at four times 50m trials in back crawl and front crawl at the same testing speeds. ** $p < 0.01$, * $p < 0.05$

4.3.12. Vertical Displacement of the Knee

4.3.12.1. Mean Vertical Displacement of the Knee

Figure 4.59 shows the mean vertical (y) displacement of the knee during the stroke cycle in BC and FC@BC. There were no significant differences in the vertical knee displacement between BC and FC@BC with small-medium effect sizes (trial-1: $d=0.23$, trial-2: $d=0.40$, trial-3: $d=0.59$, trial-4: $d=0.63$). There were significant main effects of the trial on the mean vertical displacement of the knee with large effect sizes in both BC ($p<0.01$, $\omega^2=0.76$) and FC@BC ($p<0.01$, $\omega^2=0.38$).

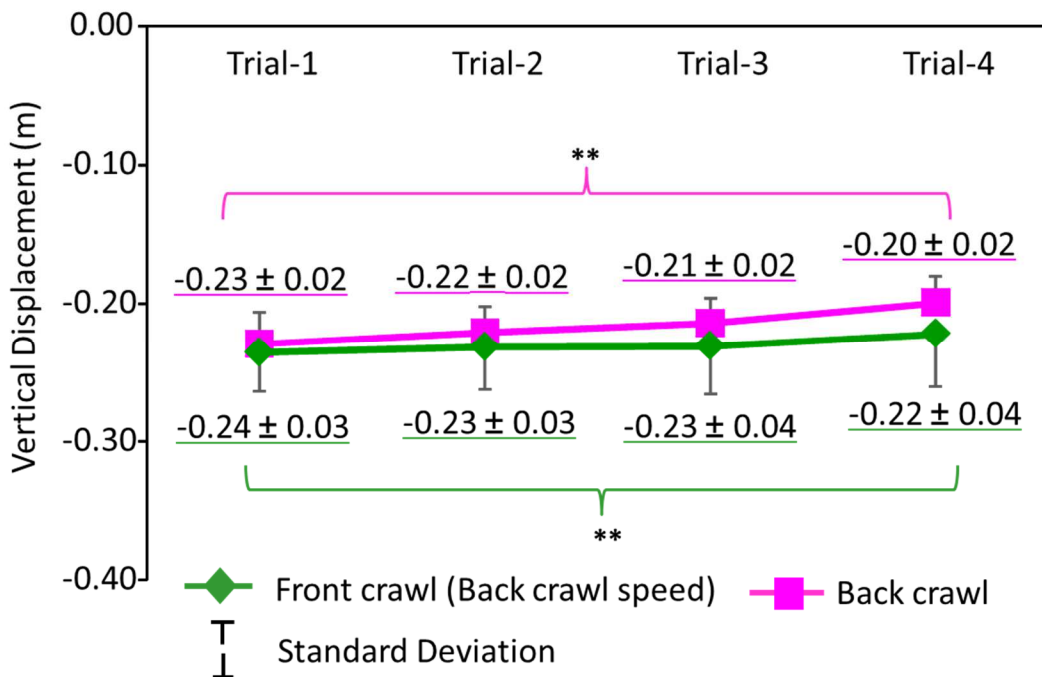


Figure 4. 59: Mean vertical displacement of the knee at four times 50m trials in back crawl and front crawl at the same testing speeds. ** $p<0.01$

4.3.12.2. Minimum Vertical Displacement of the Knee

Figure 4.60 shows the minimum vertical (y) displacement of the knee during the stroke cycle in BC and FC@BC. There were no significant differences between BC and FC@BC at any trials, and the effect sizes were small (trial-1: $d=0.01$, trial-2: $d=0.14$, trial-3: $d=0.05$, trial-4: $d=0.08$). There were significant main effects of the trial on the minimum vertical displacement of the knee with large effect sizes in both BC ($p<0.01$, $\omega^2=0.79$) and FC@BC ($p<0.01$, $\omega^2=0.68$).

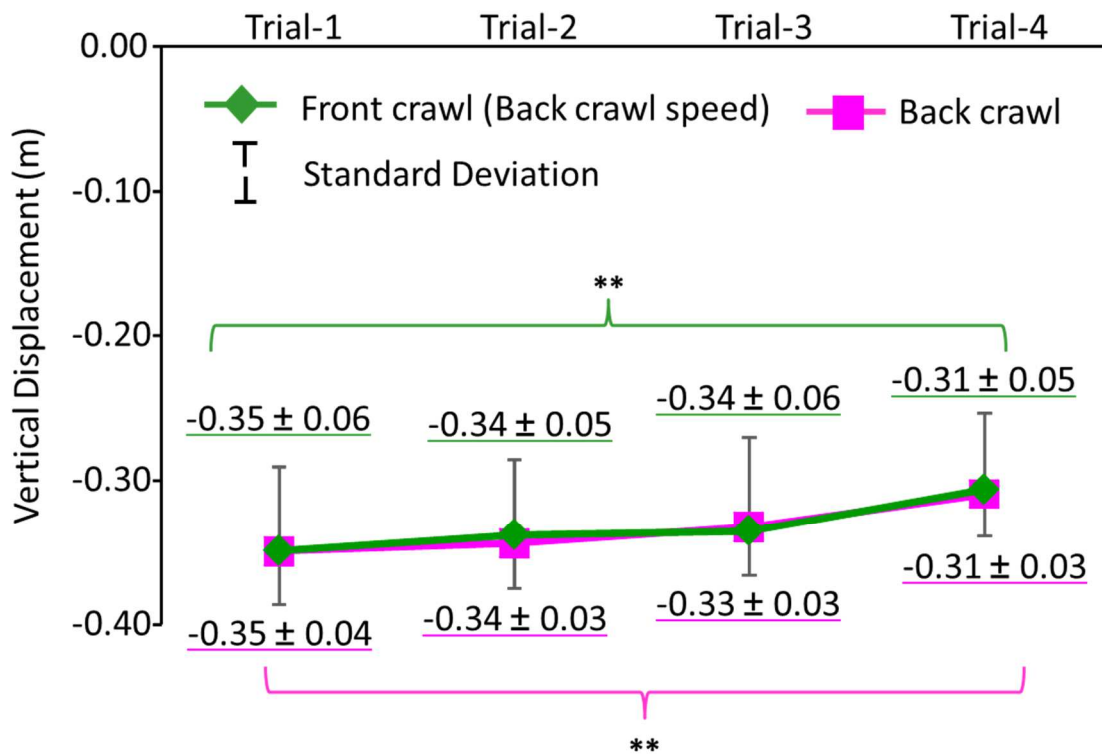


Figure 4. 60: Minimum vertical displacement of the knee at four times 50m trials in back crawl and front crawl at the same testing speeds. ** $p<0.01$, * $p<0.05$

Results Four-Four

Results from Study 3

4.4. Results from Study 3

In this section, the results from 4×50-m trials in front crawl and back crawl at the same selected speeds, and isokinetic torque measurement are presented.

4.4.1. Race Parameters

4.4.1.1. Mean Speed of the COM

Figure 4.61 shows mean speeds of the COM (V) of the 4×50-m front crawl (FC) trials and back crawl (BC) trials. V in FC was significantly larger than that in BC in all four trials ($p<0.01$). In both FC and BC, the main effects of the trials on V were significant ($p<0.01$), and both main effects showed large effect size (FC: $\omega^2=0.41$, BC: $\omega^2=0.60$).

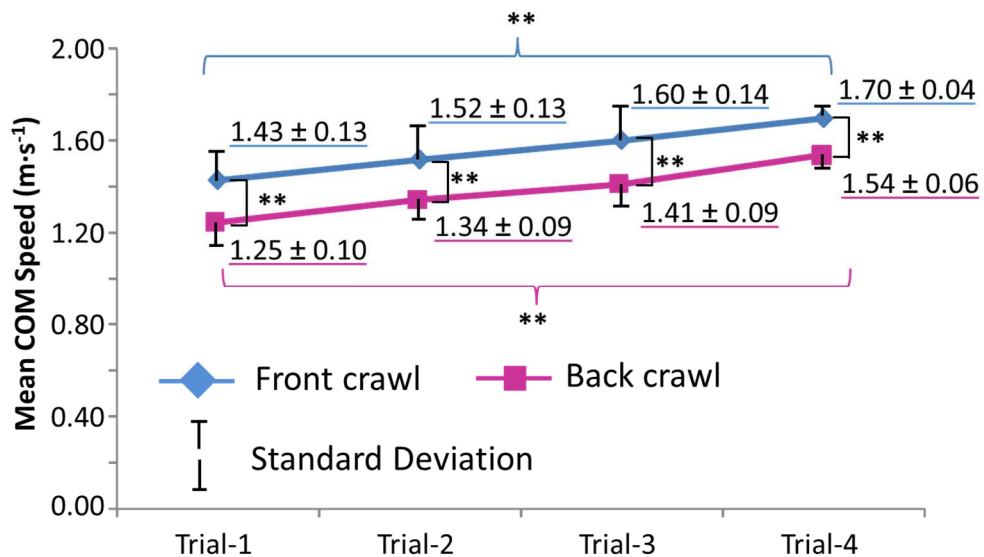


Figure 4. 61: Mean COM speeds of the swimmers at four times 50m front crawl and back crawl at the same exercise intensities. ** $p<0.01$

4.4.1.2. Stroke Frequency

Figure 4.62 shows stroke frequency (*SF*) at the 4×50-m trials in FC and BC. *SF* in FC was significantly higher than that in BC in all four trials (trial-1 and trial-3: $p < 0.04$, trial-2 and trial-4: $p < 0.01$). Effect sizes of these differences were medium in trial-1 ($d = 0.76$) and large in trial-2 ($d = 1.11$), trial-3 ($d = 0.86$), and trial-4 ($d = 1.23$). There were significant main effects of trials on *SF* in both FC and BC ($p < 0.01$) with large effect sizes (FC: $\omega^2 = 0.53$, BC: $\omega^2 = 0.59$).

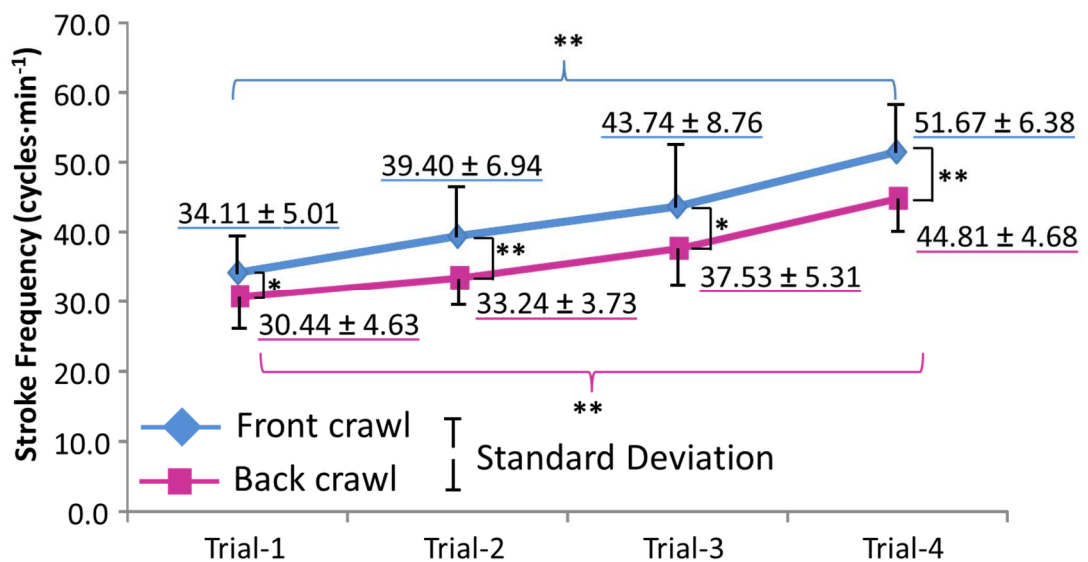


Figure 4. 62: Stroke frequency of the swimmers at four times 50m front crawl and back crawl at the same exercise intensities. ** $p < 0.01$, * $p < 0.04$

4.4.1.3. Stroke Length

Figure 4.63 shows stroke length (*SL*) of FC and BC at the 4×50-m trials. There was no difference between FC and BC at each trial. In both FC and BC, there were significant main effects of trials on *SL* ($p < 0.01$) with large effect sizes (FC: $\omega^2 = 0.34$, BC: $\omega^2 = 0.37$)

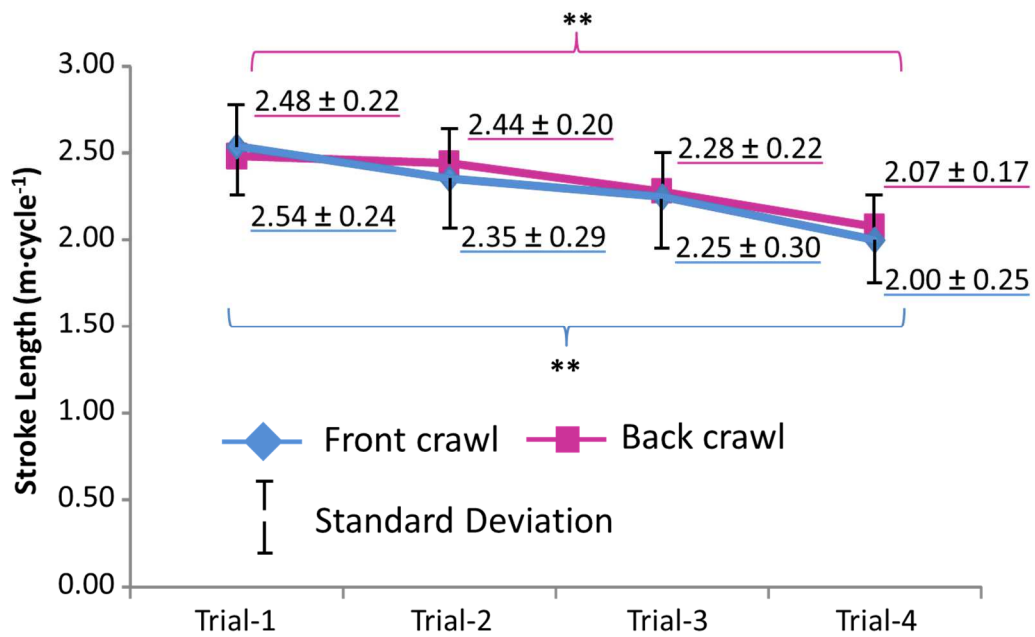


Figure 4. 63: Stroke length of the swimmers at four times 50-m front crawl and back crawl at the same exercise intensities. ** $p < 0.01$

4.4.2. Duration of the Phase

4.4.2.1. Duration of Each Phase

Figure 4.64 shows the duration of each phase (Entry, Pull, Push, Release, and Above-water) of the swimmers in all trials. In all trials, swimmers spent significantly longer duration in the release and above-water phases in BC than those in FC ($p < 0.01$). On the other hand, the duration of the entry phase in FC was significantly longer than that in BC ($p < 0.01$).

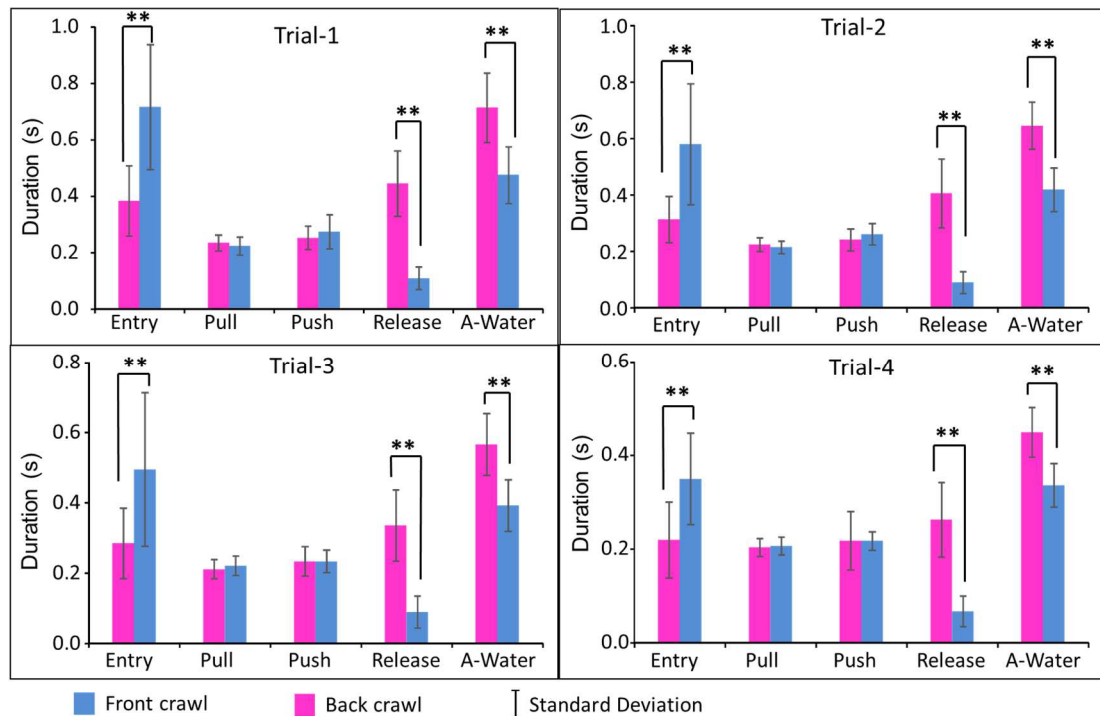


Figure 4. 64: Duration of each phase at four times 50m trials in front crawl and back crawl at the same exercise intensities. ** $p < 0.01$, * $p < 0.05$

Figure 4.65 shows the relationship between swimming speed (trials) and relative phase durations.

There were significant main effects of the trial on relative duration phase in the pull ($p < 0.01$), push ($p < 0.05$), and above-water ($p < 0.01$) phase in BC, the entry ($p < 0.01$), pull ($p < 0.01$), and push ($p < 0.01$) phase in FC. The effect sizes of these main effects are medium in the pull phase ($\omega^2 = 0.09$), medium in the push phase ($\omega^2 = 0.09$), and small-medium in the above-water phase ($\omega^2 = 0.04$) in BC, large in the entry phase ($\omega^2 = 0.45$), nearly large in the pull phase ($\omega^2 = 0.13$), and small-medium in the push phase ($\omega^2 = 0.04$) in FC.

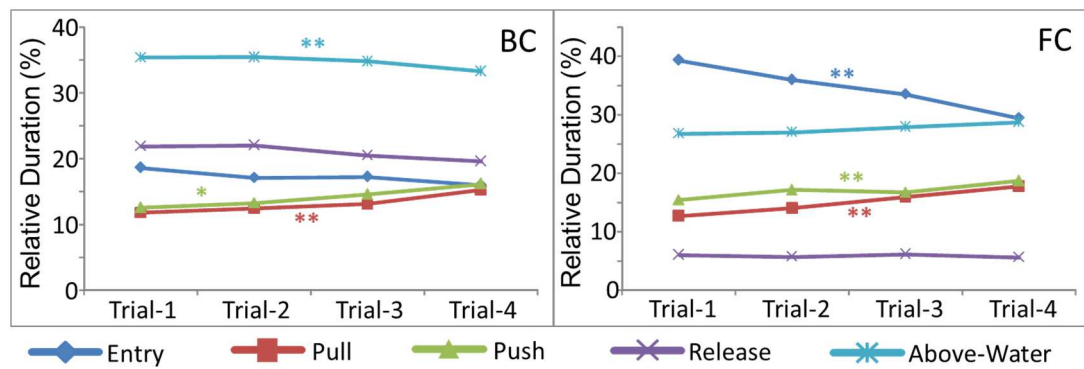


Figure 4. 65: Significant main effects of trials on the duration of each phase relative to stroke cycle time at four times 50m trials in front crawl and back crawl at the same exercise intensities. ** $p < 0.01$, * $p < 0.05$

4.4.2.2. Duration of Propulsive and Non-Propulsive Phases

Figure 4.66 shows the absolute duration of the propulsive phases (the pull and push phases). There were no differences in the duration of the propulsive phases between front crawl and back crawl. Figure 4.67 shows the absolute duration of the non-propulsive phases (the entry, release, and above-water phases). In all trials, the non-propulsive phases in BC was significantly longer than that in FC ($p < 0.05$) with large effect sizes (trial-1: $d = 0.88$, trial-2: $d = 1.16$, trial-3: $d = 0.84$, trial-4: $d = 1.44$).

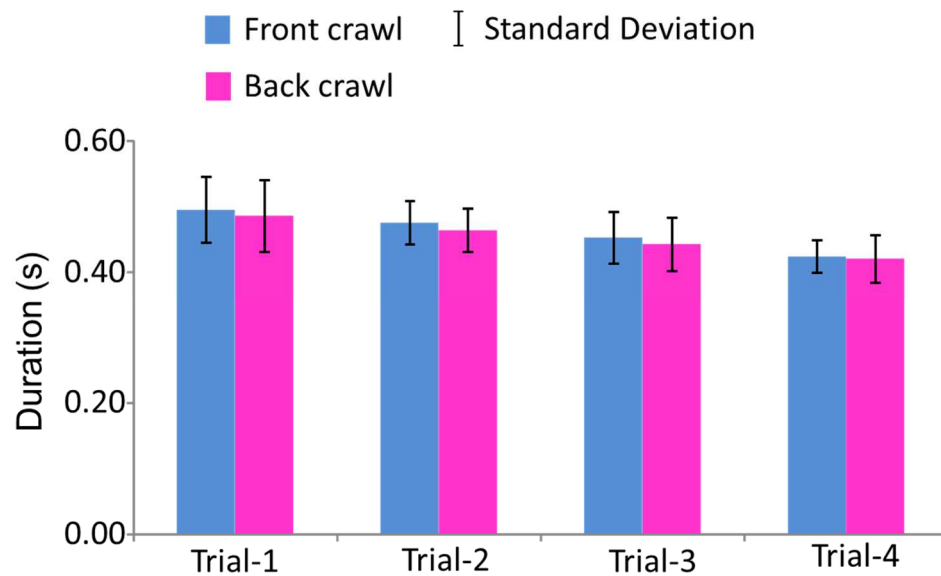


Figure 4. 66: The absolute duration of the propulsive phase during the stroke cycle at four times 50m trials in back crawl and front crawl at the same exercise intensities. ** $p < 0.01$. * $p < 0.05$

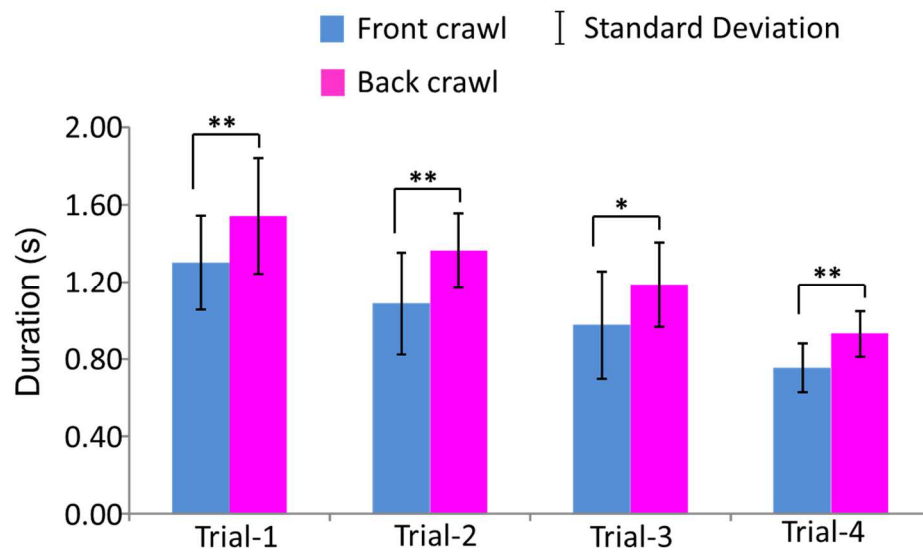


Figure 4. 67: The absolute duration of the non-propulsive phase during the stroke cycle at four times 50m trials in back crawl and front crawl at the same exercise intensitiesp<0.01. *p<0.05**

4.4.3. Shoulder and Hip Roll Angle

4.4.3.1. Maximum Shoulder Roll Angle

Figure 4.68 shows maximum shoulder roll angle of swimmers in FC and BC. Swimmers had larger maximum shoulder angle in FC than in BC in trial-1 ($p < 0.01$) and trial-2 ($p < 0.05$) and the size of the effects were large and medium (trial-1: $d = 1.66$ trial-2: $d = 0.66$). There was a significant main effect of trials on maximum roll angle in FC with a nearly large effect size, but not in BC ($p < 0.01$, $\omega^2 = 0.13$).

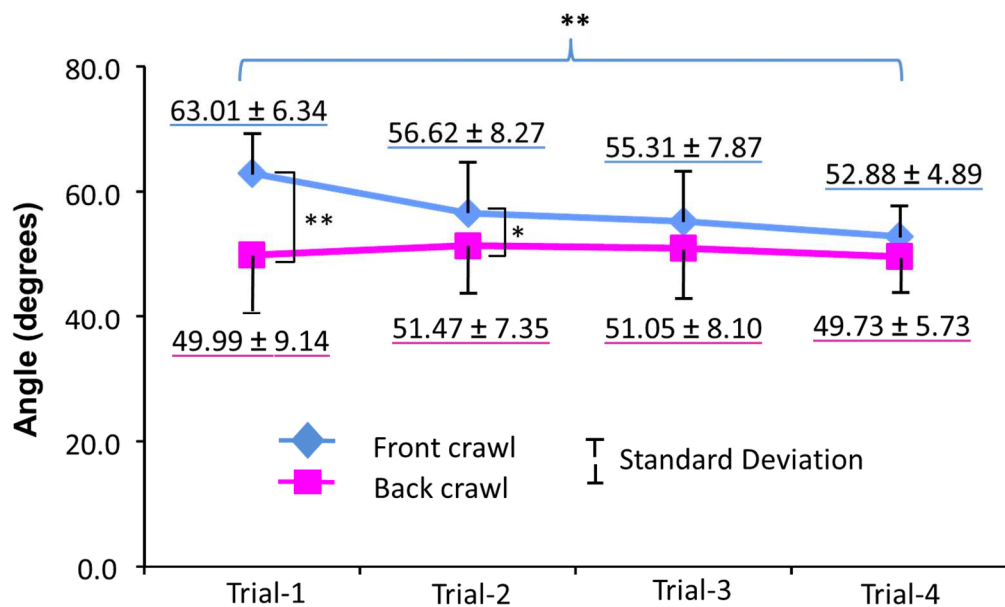


Figure 4. 68: Maximum shoulder roll angle during the stroke cycle at four times 50m trials in back crawl and front crawl at the same exercise intensities. ** $p < 0.01$, * $p < 0.05$

4.4.3.2. Maximum Hip Roll Angle

Figure 4.69 shows maximum hip roll angle of swimmers in FC and BC. Swimmers had larger hip roll angle in FC than in BC with a large effect size ($p < 0.05$, $d = 0.90$) in trial-1. However, swimmers had smaller hip roll angle in FC than in BC in trial-4 with a large effect size ($p < 0.05$, $d = 0.90$). There was a significant main effect of trials on maximum hip roll angle in FC with a large effect size ($p < 0.01$, $\omega^2 = 0.38$), but not in BC.

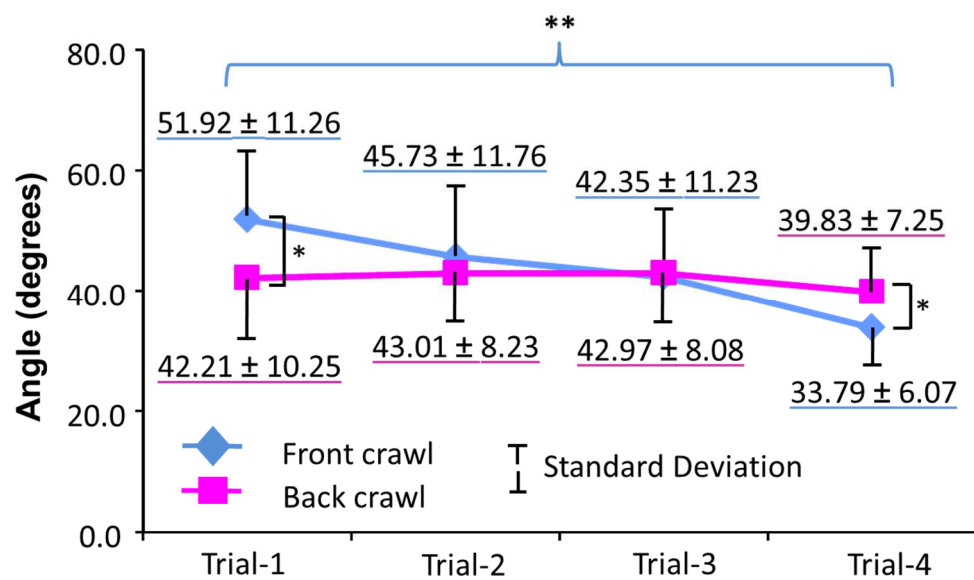


Figure 4. 69: Maximum hip roll angle during the stroke cycle at four times 50m trials in back crawl and front crawl at the same exercise intensities. ** $p < 0.01$, * $p < 0.05$

4.4.4. 3D Hand Path Distance

4.4.4.1. 3D Hand Path Distance during the Underwater Phase

Figure 4.70 shows the distance of the 3D hand path in FC and BC. Swimemrs had significantly longer hand path distance in BC than in FC with large effect sizes (trial-1: $p < 0.01$, $d = 1.27$, trial-2: $p < 0.01$, $d = 1.16$, trial-3: $p < 0.05$, $d = 1.02$, trial-4: $p < 0.05$, $d = 0.88$).

There were significant main effects of the trial on the 3D hand path distance in both FC and BC with effect sizes ranging from middle to large (FC: $p < 0.01$, $\omega^2 = 0.08$, BC: $p < 0.01$, $\omega^2 = 0.14$).

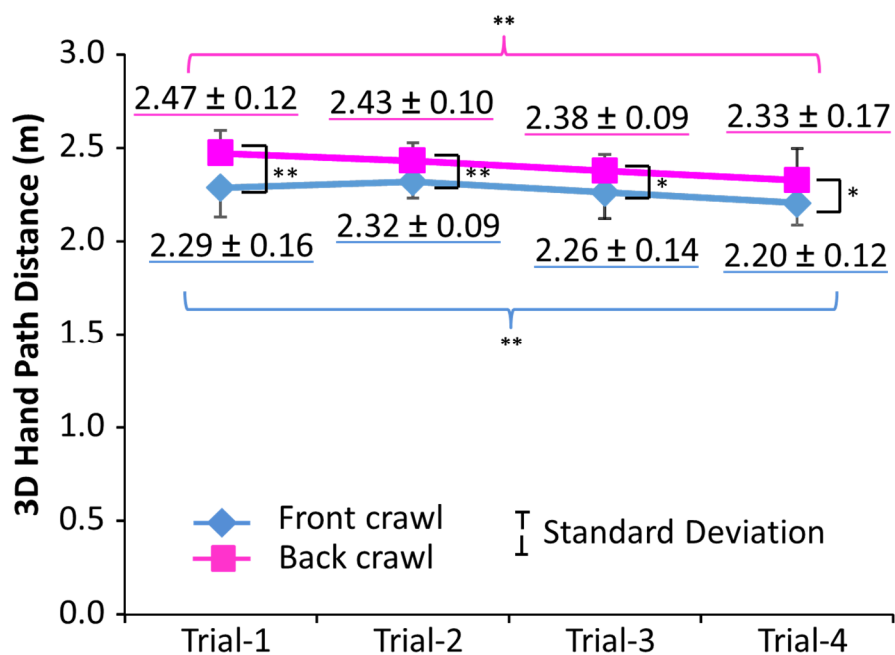


Figure 4. 70: Underwater 3D hand path distance during the stroke cycle at four times 50m trials in back crawl and front crawl at the same exercise intensities. ** $p < 0.01$, * $p < 0.05$

4.4.4.2. 3D Hand Path Distance during Each Phase

Figure 4.71 shows the distance of 3D hand path in each trial. 3D hand path in BC was significantly longer than that in FC during the release and above-water phases in all trials with large effect sizes ($d > 2.73$). The 3D hand path distance in BC was significantly shorter than that in FC during the entry phase at all trials with large effect sizes ($d > 1.86$). Swimmers had significantly shorter 3D hand path distance in BC than that in FC during the push phase at trial-2 and trial-4 with large effect sizes (trial-2: $d = 1.64$, trial-4: $d = 1.50$).

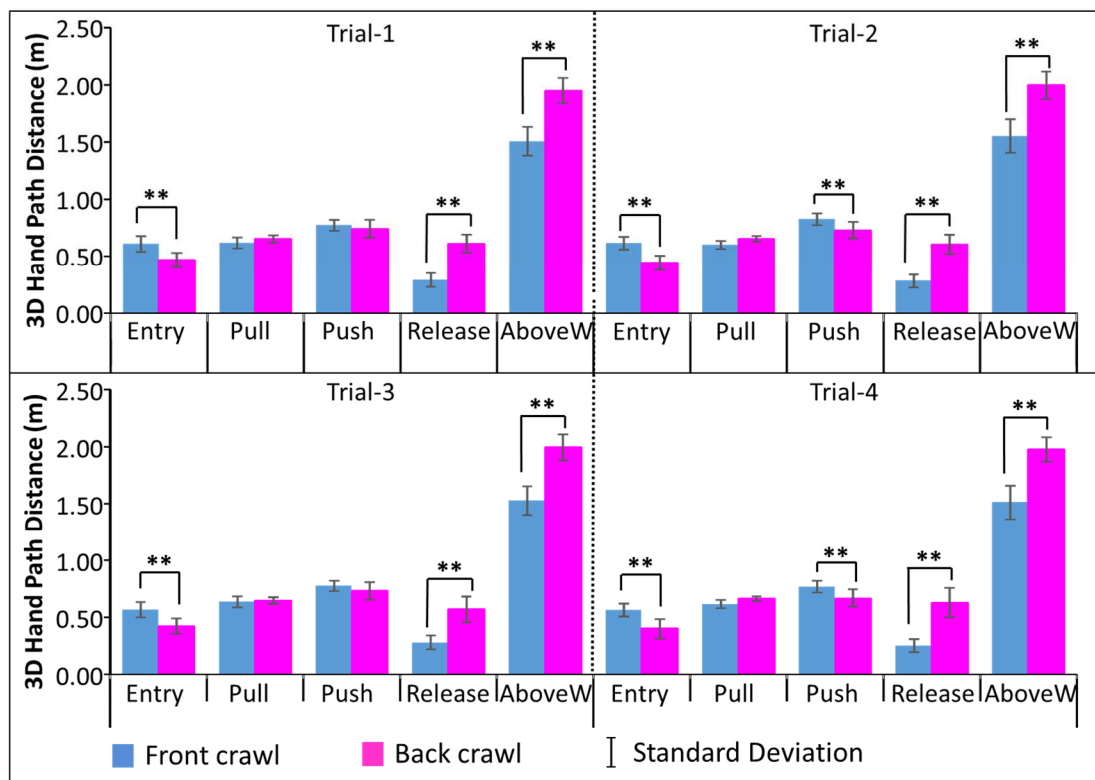


Figure 4. 71: 3D hand path distance during each phase at four times 50m trials in back crawl and front crawl at the same exercise intensities. ** $p < 0.01$, * $p < 0.05$

4.4.5. Joint Angle

4.4.5.1. Elbow Joint Angle during the Pull and Push Phases

Figure 4.72 shows maximum, mean, and minimum elbow joint angle during the pull phase in FC and BC. There were no significant difference between FC and BC and no significant main effects of the trial on the elbow joint angle.

Figure 4.73 shows elbow joint angle during the push phase. There were significant main effects of trials on maximum, mean, and minimum elbow joint angle in BC (maximum and mean angle: $p < 0.05$, minimum angle: $p < 0.01$). The sizes of the main effects in maximum and minimum elbow angle were medium (max: $\omega^2 = 0.10$, minimum: $\omega^2 = 0.13$), and the size of the effect of mean elbow angle was large ($\omega^2 = 0.19$). There were also significant differences in the elbow joint angle between FC and BC ($p < 0.05$).

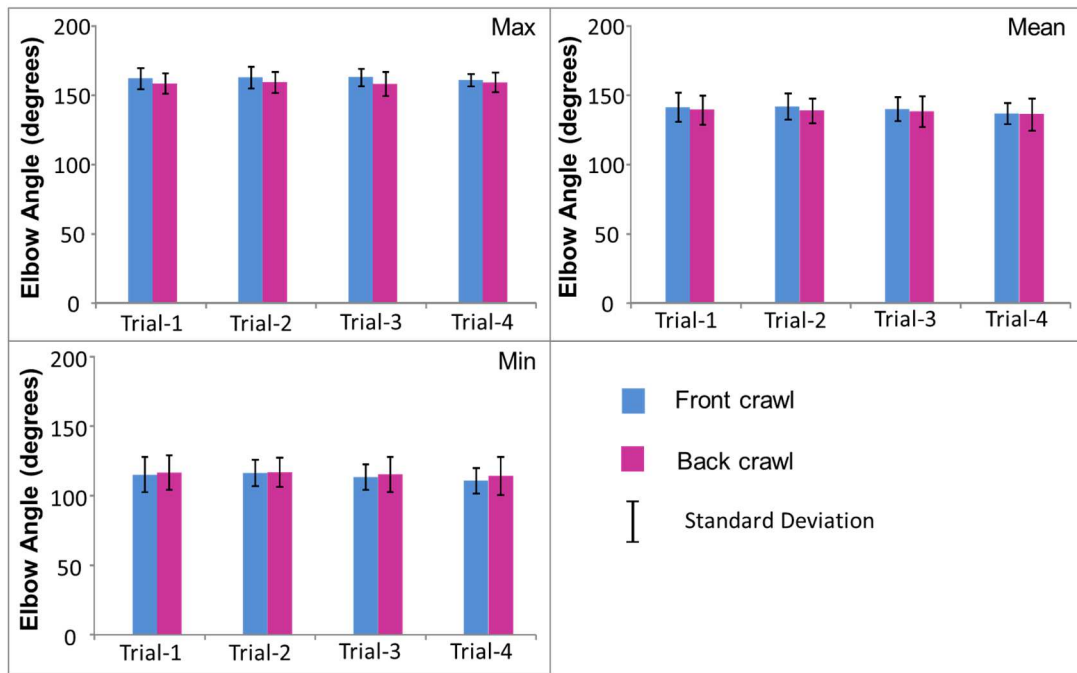


Figure 4.72: Maximum, minimum, and mean elbow joint angle during the pull phase at four times 50m trials in back crawl and front crawl at the same exercise intensities.

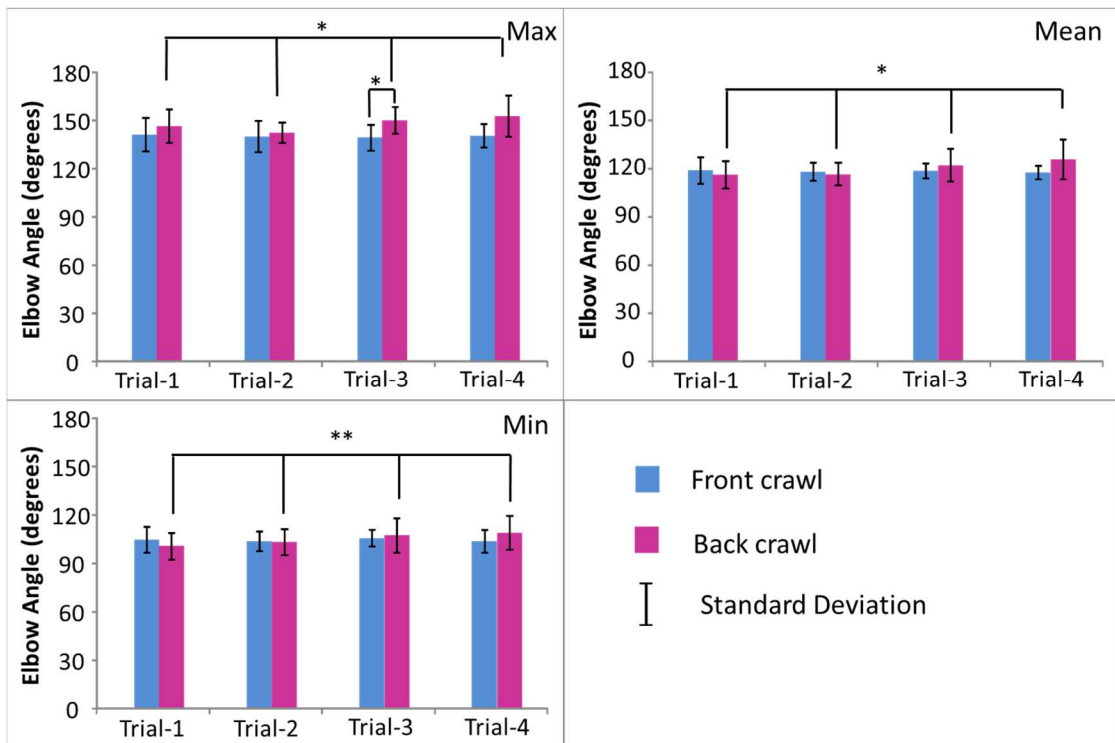


Figure 4.73: Maximum, minimum, and mean elbow joint angle during the push phase at four times 50m trials in back crawl and front crawl at the same exercise intensities. ** $p < 0.01$, * $p < 0.05$

4.4.5.2. Mean Shoulder Horizontal Abduction Angle during the Pull Phase

Figure 4.74 shows the mean shoulder horizontal abduction angle during the pull phase in FC, and BC. There were no differences between each stroke, and there were no significant main effects of the trial on the horizontal abduction angle. The angle ranged from 156 to 164 degrees in FC, and from 154 to 169 degrees in BC.

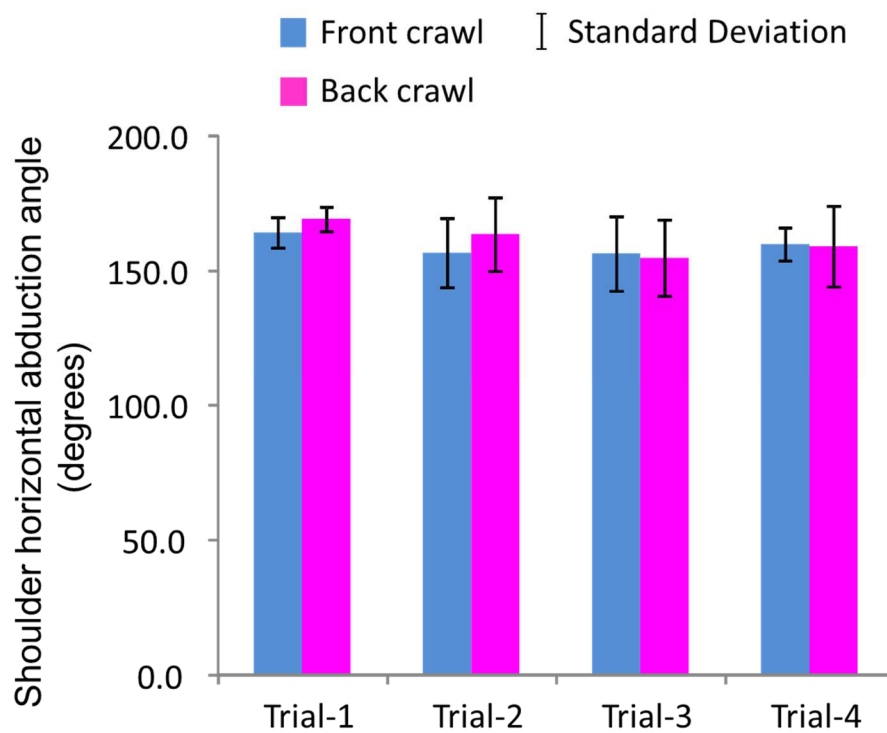


Figure 4. 74: Mean shoulder horizontal abduction angle during the pull phase at four times 50m trials in back crawl and front crawl at the same exercise intensities.

4.4.5.3. Mean Shoulder Horizontal Abduction Angle during the Push Phase

Figure 4.75 shows the mean shoulder horizontal abduction angle during the push phase in FC and BC. The mean shoulder horizontal abduction angle in BC was significantly larger than that in FC at all trials with large effect sizes (trial-1: $p < 0.01$, $d = 3.97$, trial-2: $p < 0.01$, $d = 2.48$, trial-3: $p < 0.01$, $d = 1.57$, trial-4: $p < 0.05$, $d = 1.47$). The angle ranged from 126 to 137 degrees in FC, and from 157 to 164 degrees in BC.

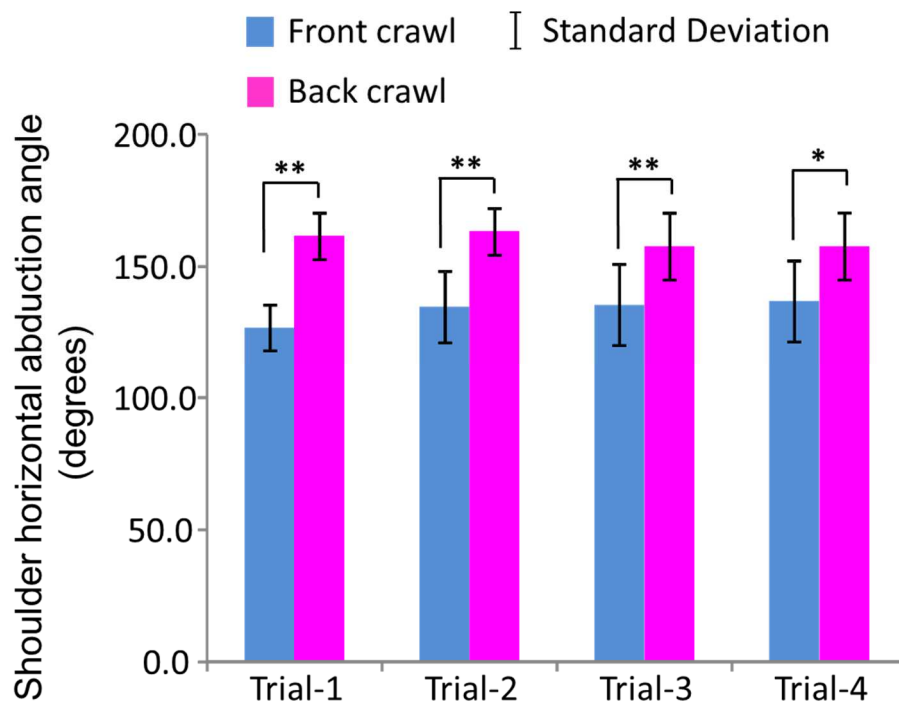


Figure 4. 75: Mean shoulder horizontal abduction angle during the push phase at four times 50m trials in back crawl and front crawl at the same exercise intensities. ** $p < 0.01$, * $p < 0.05$

4.4.6. Timing Index

Figure 4.76 shows the timing index (the timing of the hand entry in relation to the percentile of the underwater phase of the other hand) of FC and BC. Swimmers had significantly larger timing index in BC than in FC with large effect sizes at trial-1 ($p < 0.01$, $d = 1.92$), trial-2 ($p < 0.01$, $d = 1.60$), and trial-3 ($p < 0.01$, $d = 1.09$), which means swimmers hand entry is relatively earlier in FC than in BC. Although there was no significant difference in the timing index between FC and BC at trial-4 ($p = 0.09$), the effect size was large ($d = 0.96$). There were no significant main effects of the trial on the timing index in both strokes, and the effect sizes were small ($\omega^2 < 0.01$)

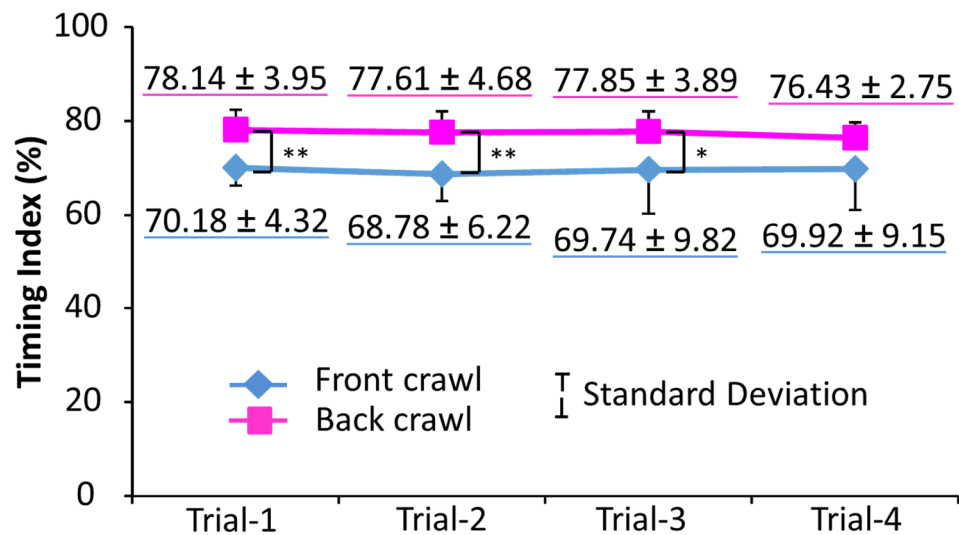


Figure 4. 76: Timing index during the stroke cycle at four times 50m trials in back crawl and front crawl at the same exercise intensities. ** $p < 0.01$, * $p < 0.05$

4.4.7. Shoulder Isokinetic Torques

4.4.7.1. Shoulder Adduction Torque and Shoulder Extension Torque

Figure 4.77 and Figure 4.78 show differences in peak torque (PT), the percentile of peak torque relative to the body weight (PT/BW), the mean value of the peak torque in each repetition (Mean PT), and total work (TW) values (mean values of left limb torque and right limb torque) between shoulder extension and shoulder adduction at 60 deg·s⁻¹ and 180 deg·s⁻¹ trials respectively. Swimmers had significantly larger shoulder extension (which has been supposed to be used predominantly in FC: Miyashita & Kanehisa, 1979) isokinetic torque than shoulder adduction (which has been supposed to be used predominantly in BC: Perry et al., 1992; Pink et al., 1992) isokinetic torque at both 60 deg·s⁻¹ (PT: p<0.01, d=0.81, PT/BW: p<0.01, d=0.98, Mean PT: p<0.01, d=0.77, TW: p<0.04, d=0.43) and 180 deg·s⁻¹ (PT: p<0.02, d=0.94, PT/BW: p<0.02, d=0.95, Mean PT: p<0.01, d=1.14, TW: p<0.01, d=0.65). There were large effect sizes in PT and PT/BW at 60 deg·s⁻¹ trial, and PT, PT/BW and Mean PT at 180 deg·s⁻¹ trial. The size of the effect in Mean PT at 60 deg·s⁻¹ trial and TW at 180 deg·s⁻¹ trial were medium. Although there was significant difference between shoulder extension and adduction in TW at 60 deg·s⁻¹ trial, the size of the effect was small.

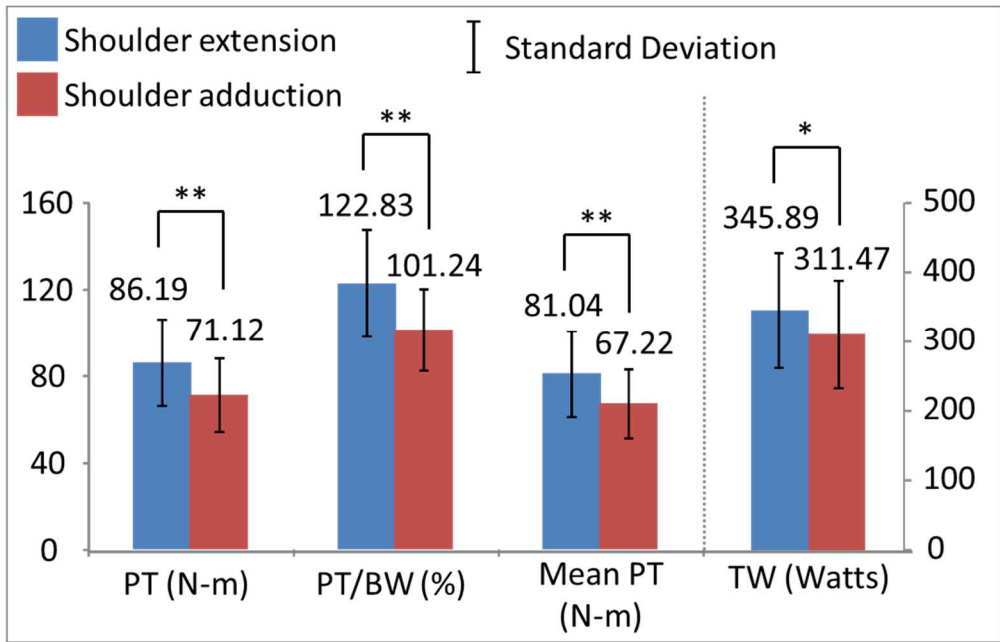


Figure 4. 77: Shoulder extension and adduction isokinetic torque values and total work of the swimmers at 60 deg·s⁻¹ trials. **p<0.01, *p<0.05

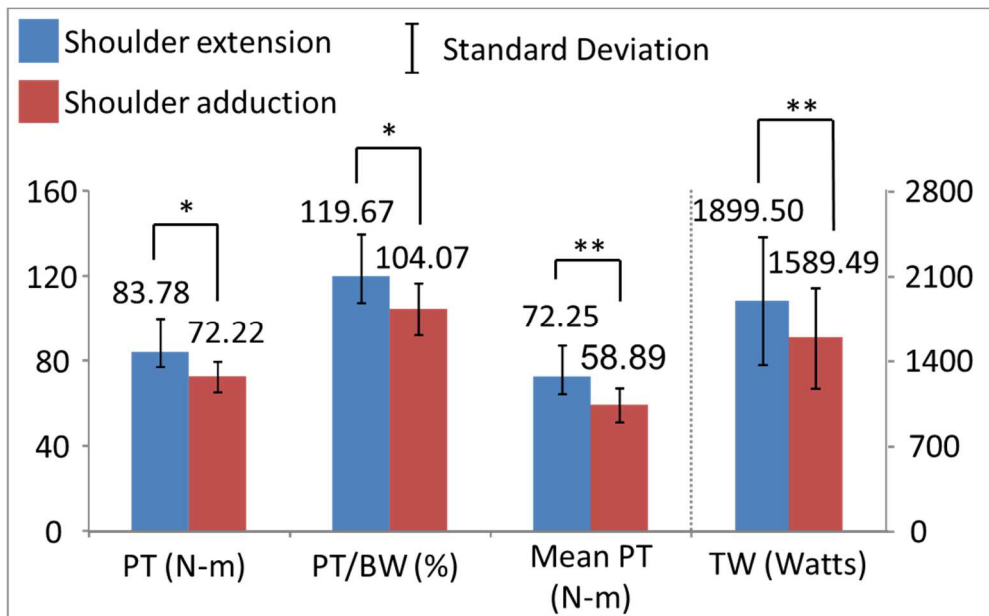


Figure 4. 78: Shoulder extension and adduction isokinetic torque values and total work of the swimmers at 180 deg·s⁻¹ trials. **p<0.01, *p<0.05

4.4.7.2. Correlation between Isokinetic Torque Values and Kinematics Values

Table 4.3 shows the significant correlations between isokinetic torque values and stroke parameters in the fastest trial (trial-4) of the 4×50-m FC and BC. The reported correlation coefficient values in the table are mean values of correlation coefficient between kinematic variables and left isokinetic torque variables and between kinematic variables and right isokinetic torque variables. At the significant level of 1%, there were significant positive correlations between *SF* and adduction PT/BW at 180 deg·s⁻¹ in both FC and BC, and there were significant negative correlations between adduction PT/BW at 180 deg·s⁻¹ and *SL* in FC, *SI* in FC, and *SL* in BC ($p < 0.01$). There was also a significant negative correlation between internal rotation PT/BW at 60 deg·s⁻¹ and the duration of the underwater phase in FC. There were significant negative correlations between adduction PT/BW at 180 deg·s⁻¹ and normalised *SL* in FC and BC.

At the significant level of 5%, there were significant correlation between shoulder flexion PT/BW at 180 deg·s⁻¹ and *SF*, *SL*, normalised *SL* and *SI* in FC. There was also a significant correlation between internal rotation PT/BW at 180 deg·s⁻¹ and the duration of the underwater phase in FC. Significant correlations were also observed between the normalised *SL* and shoulder extension and internal PT/BW at 180 deg·s⁻¹. There were significant negative correlations between extension PT/BW at 180 deg·s⁻¹ and normalised *SL* in FC, and between internal rotation PT/BW at 180 deg·s⁻¹ and normalised *SL* in FC.

Although correlation analysis between total work in isokinetic torque measurements and kinematic variables was conducted, no significant correlations were observed between any variables.

Table 4. 3: Significant correlations between isokinetic torque variables and kinematic variables at the 130%*v*OBLA trials in front crawl and back crawl. * $p < 0.05$, ** $p < 0.01$

Person's Correlation (N=10)	Abduction	Adduction	Internal	Internal	Extension	Flexion
	180 deg·s ⁻¹ PT/BW	180 deg·s ⁻¹ PT/BW	60 deg·s ⁻¹ PT/BW	180 deg·s ⁻¹ PT/BW	180 deg·s ⁻¹ PT/BW	180 deg·s ⁻¹ PT/BW
Stroke Frequency FC	0.64*	0.85**	-	-	-	0.67*
Stroke Length FC	-0.70*	-0.85**	-	-	-	-0.72*
Stroke Length (Normalised) FC	-	-0.79**	-0.66*	-	-0.63*	-0.73*
Stroke Index FC	-0.74*	-0.79**	-	-	-	-0.72*
Stroke Frequency BC	0.67*	0.87**	-	-	-	-
Stroke Length BC	-0.72*	-0.80**	-	-	-	-
Stroke Length (Normalised) BC	-	-0.66*	-	-	-	-
Stroke Index BC	-	-	-	-	-	-
Duration-UW FC	-	-0.82**	-0.79**	-0.76*	-	-
Duration-UW BC	-0.69*	-0.88**	-	-	-	-

Results Four-Five

Summary of the Results

4.5. Summary of the Results from Study 1, Study 2 and Study 3

4.5.1. The Differences between Front Crawl and Back Crawl at the Same Speed below the Anaerobic Threshold

Under the anaerobic threshold, the energy expenditure of the swimmers in back crawl (BC) was significantly higher than that of front crawl (FC) at the same speed. However, there were no significant differences in race parameters. There was no difference in the intra-cycle velocity variation in swimming direction (IVV_x), intra-cycle maximum velocity (IV_{max}) and intra-cycle minimum velocity (IV_{min}) between FC and BC. Swimmers' foot path distance and the range of motion of the foot in vertical-direction was larger in BC than those in FC.

The duration of the entry phase of FC was longer than that of BC, whereas the duration of the release and above-water phase in BC were longer than those of FC. There were no significant differences in the duration of the pull and push phases between FC and BC. There were no differences in the hand speed in swimming direction during the pull and push phases between FC and BC, although the effect sizes were large. Swimmers also had larger hand acceleration during the pull phase, and larger hand deceleration during the push phase in BC than in FC. Swimmers also had larger 3D hand path distance relative to the centre of mass (COM), and faster mean 3D hand speed relative to COM during the stroke cycle in BC than in FC. Swimmers had significantly higher Froude efficiency (η_F) in FC than in BC.

Swimmers had larger maximum shoulder and hip roll angle in FC than in BC. There was no significant difference in yaw angle fluctuation between FC and BC, however, the effect size was large. Swimmers also had larger maximum lateral distance between the hand and COM in BC than in FC.

Swimmer's mean and maximum vertical displacement of COM in BC was smaller (which means deeper vertical displacement of COM relative to the water surface) than those in FC.

The mean vertical displacements of the mid-shoulder and mid-foot during the stroke cycle were smaller (deeper relative to the water surface) in BC than in FC.

4.5.2. Kinematic Differences between Front Crawl and Back Crawl at the Same Selected Speeds above the Anaerobic Threshold

At the same speed, Swimmers had larger stroke index (*SI*) and longer stroke length (*SL*) in FC than in BC at all four trials except *SL* in trial-1. The effect size of the difference in *SL* in trial-1 was yet nearly large. The duration of the propulsive phases (the pull and push phases) in FC was longer than that in BC with large effect sizes, although the difference at trial-1 was not significant.

The mean hand speed in swimming direction during push phase in BC was significantly faster than that in FC. Swimmers also had larger hand acceleration during the pull phase, and larger hand deceleration during the push phase in BC than in FC.

The *IVV_x* in BC was larger than that in FC at trial-3, and trial-4 with large effect sizes. The intra-cycle minimum velocity (*IV_{min}*) in FC was significantly faster than that in BC in trial-2, trial-3, and trial-4.

The mean vertical displacement of the foot of the swimmers in FC was significantly larger (closer to the water surface) than in BC.

Swimmers had significantly larger maximum shoulder roll angle in FC than in BC at all trials. Swimmers also had significantly larger hip roll angle in FC than in BC at trial-1, trial-2, and trial-3. There were significant main effects of the trial on the shoulder and hip roll angles in FC, but not in BC.

Swimmers had significantly higher η_F in FC than BC at all trials, and the mean 3D hand speed relative to COM ($3Du$) in BC was significantly faster than that in FC. The product of the mean 3D hand speed during a phase ($3Du_{phase}$) and the duration (d) of the phase relative to the stroke cycle (Contribution factor: $\frac{3Du_{phase} \cdot d_{phase}}{d_{stroke\ cycle}}$) in BC was larger than that in FC in the pull, release, and above-water phase (which means these phases positively contributed to the faster $3Du_{SC}$ in BC than in FC).

4.5.3. Kinematic Differences between Front Crawl and Back Crawl at the Same Selected Exercise Intensities above the Anaerobic Threshold

At the same exercise intensity, there were no significant differences in SL between FC and BC, while V and SF in FC were larger than those in BC. There were no differences in absolute duration of the pull and push phases between FC and BC.

Also, swimmers had longer 3D hand path distance relative to COM in BC than in FC in both during the underwater, and above the water phases. In the underwater phases, the phase in which swimmers had longer hand path distance in BC than in FC was the release phase.

Swimmers had significantly larger timing index in BC than in FC with large effect sizes at trial-1, trial-2, and trial-3. Although there was no significant difference in the timing index between FC and BC at trial-4, the timing index was large in BC than in FC with a large effect size. These results indicated that the swimmers entered their hand in the water later in BC than in FC in relation to the underwater phase of other hand.

There were no significant differences in the mean shoulder horizontal abduction angle during the pull phase between FC and BC. However, the mean shoulder horizontal abduction angle during the push phase in BC was significantly larger than that in FC in all trials.

There were no significant differences in elbow joint angle of the swimmer between FC and BC during both pull and push phases, and the mean elbow angle varied from 135 to 142 degrees during the pull phase, and from 116 to 126 degrees during the push phase.

4.5.4. The Relationships between Isokinetic Torques and Front and Back Crawl

At the significance level of $p < 0.01$, there was significant strong positive correlations between the adduction peak torque relative to the body weight at $180 \text{ deg} \cdot \text{s}^{-1}$ and *SF* in both strokes. There were also significant negative correlations between the adduction peak torque relative to the body weight at $180 \text{ deg} \cdot \text{s}^{-1}$ and *SL* in both strokes. There was also a significant strong correlation between adduction peak torque relative to the body weight at $180 \text{ deg} \cdot \text{s}^{-1}$ and *SI* in FC. There was a significant negative correlations between internal peak torque relative to the body weight at $60 \text{ deg} \cdot \text{s}^{-1}$ and the duration of the underwater phase in FC. There was a significant negative correlation between the adduction peak torque relative to the body weight at $180 \text{ deg} \cdot \text{s}^{-1}$ and the duration of the underwater phase in BC. There were also significant negative correlations between normalised *SL* in both FC and BC and the adduction peak torque relative to the body weight at $180 \text{ deg} \cdot \text{s}^{-1}$.

Chapter Five
Discussion

5.1. Discussion – Accuracy and Reliability of Digitising

The low values of coefficient of variation (*CV*) in most of the variables suggested the kinematic variables calculated in this study were reliable. However, large *CV* values (larger than 5%) were observed in intra-cycle velocity variation (front crawl: 10.99%, back crawl: 8.43%), net impulse (front crawl: 7.91%, back crawl: 9.36%), and yaw angle fluctuation (front crawl: 5.66%, back crawl: 5.73%). These results suggested that differences in these variables which are smaller than the abovementioned percentage might be caused by the digitising errors in this study.

In front crawl, *CV* of the duration, 3D hand path distance, and contribution factor of the release phase in front crawl were also very large. This was due to the small mean values of these variables. In fact, *CV* of these variables in back crawl were small even though the standard deviation values were similar to the values in front crawl. Yet it should be noted that differences in these variables between front crawl and back crawl smaller than 0.02s, 0.02m, and 0.01 (standard deviation of each variables in the reliability test) respectively might be due to the digitising error in this study. Nevertheless, the differences in these variables in this study were larger than these standard deviation values (duration: 0.17-0.32 seconds, 3D hand path distance: 0.30-0.35m, contribution factor: 0.18-0.26) and thus, it can be concluded that the effect of the digitising errors in the duration, 3D hand path distance, and contribution factor during the release phase on the results of this study was small.

In most of the variables, the difference between 25Hz digitising trials and 50 Hz digitising trials were less than 5%. However, net impulse had the difference larger than 5% in both front crawl (5.72%) and back crawl (6.23%). These percentages were smaller than the *CV* values of net impulse in the reliability test, and thus, it might be possible that the large differences were merely due to the digitising error. Nevertheless, considering that the standard deviation of the differences in net impulse between 25Hz digitising trials and 50Hz

digitising trials in both front crawl (1.48 N·s) and back crawl (2.76 N·s) were slightly larger than those of the reliability test (front crawl: 1.13 N·s, back crawl: 1.15 N·s), the differences should not be ignored and possibility of inaccuracy of 25Hz digitising to obtain net impulse in front crawl and back crawl should be recognised.

5.2. Discussion – Study 1: Why Is Front Crawl More Economical Than Back Crawl below the Anaerobic Threshold?

The purpose of Study 1 was to quantify both physiological and biomechanical differences at an aerobic exercise intensity to assess whether front crawl is more economical than back crawl at this intensity. This section explores the differences observed in Study 1 reported in the Results Section.

5.2.1. Differences in Energy Expenditure and Race Parameters between Front Crawl and Back Crawl.

The difference in physiological economy might be one of the reasons which explains why front crawl is faster than back crawl. In this study, the energy expenditure (\dot{E}) below the anaerobic threshold in back crawl was significantly higher by 16% than that in front crawl at the same speed with a large effect size ($d=2.40$), which means front crawl is more economical than back crawl. The accuracy of the measured energy was supported by the blood lactate values of the swimmers. In both front crawl and back crawl, the blood lactate values after the 300-m trials were lower than the blood lactate values at the anaerobic threshold (32.1% lower in front crawl, and 22.5% lower in back crawl). Since the method

used in this study could only produce accurate \dot{E} values below the anaerobic threshold, these results validated the use of this method for the calculation of energy. To investigate the difference in the energy expenditure, it was necessary to conduct the swimming trials in front crawl and back crawl at the same swimming speed. In this study, there was no difference in the swimming speed between front crawl and back crawl. However, the mean value of the swimming speed was slightly higher in front crawl than in back crawl (1.077 m·s⁻¹ in front crawl, and 1.054 m·s⁻¹ in back crawl), and the mean difference was around 2% which exceeded the digitise-redigitise errors in front crawl and back crawl (0.54 and 0.32% respectively) which suggested the possibility that the swimming speed at the analysed stroke cycles between front crawl and back crawl were not very identical. Considering that the total time of the 300m trials in front crawl and back crawl were identical with the mean difference of only 0.03 %, the mean swimming speed throughout the 300m trials were very identical. Yet, it is a potential limitation of this study that the speed during each stroke cycle varied (i.e. mean speeds during some stroke cycles were faster than the instructed speed, but slower during other stroke cycles), which suggested the possibility that kinematic variables in other stroke cycles might have been slightly different from analysed stroke cycle in this study.

\dot{E} in swimming has often been discussed in relation to stroke parameters (Barbosa et al., 2008; Poujade, Hautier, & Rouard, 2002; Zamparo et al., 2005). In a previous study by Barbosa et al. (2008), it was observed that stroke frequency had a significant positive correlation with \dot{E} required for a given distance ($R^2=0.56$, $p<0.01$ in front crawl, and $R^2=0.22$, $p=0.05$ in back crawl). In Barbosa's study, however, there was a big difference in coefficients of determination (R^2) values between front crawl and back crawl (0.56 vs 0.22) with the value for back crawl being lower. Thus, stroke frequency is not a sufficient factor to determine the difference in \dot{E} between the strokes. In fact, there were no differences in stroke frequency and stroke length between the strokes in the present study, and the results

suggested that the difference in \dot{E} between the strokes was not due to the differences in stroke frequency.

To summarise, swimmers spent greater energy in back crawl than in front crawl at speeds below the anaerobic threshold, although there were no differences in stroke frequency and stroke length between the strokes. Thus, it was considered that other kinematic and kinetic factors affected the difference in \dot{E} between the strokes. In the next section, the difference in kinematic/kinetic factors, which probably affected the difference in \dot{E} between the two strokes, are discussed using the results from 3D video analysis of front crawl and back crawl swimming below the anaerobic threshold.

5.2.2. How Do Kinematic Differences Affect the Difference of Energy Expenditure between Front Crawl and Back Crawl?

To consider kinematic and kinetic factors which affected the difference in \dot{E} , it is necessary to understand how the physiological energy is used to produce mechanical energy during swimming. Figure 5.1 shows a flow diagram which explains energy conversion in aquatic locomotion (Daniel, 1992; Zamparo et al., 2002). The proportion of the energy spent for thrust relative to the whole \dot{E} is affected by work done that does not contribute to propulsion (W_k). W_k includes the work done to move the water that does not contribute to the propulsion, and work done to move the limbs. The work done depends on the mechanical power, which is the rate of the work (\dot{W}), and the time over which power is produced. In this study, both W_k and \dot{W}_k could not be estimated since the force swimmers applied on the water could not be measured. However, the proportion of \dot{W} produced for the propulsion to the \dot{W} swimmers produced by applying force on the water (Froude efficiency: η_F) was estimated

using the ratio of the speed of the centre of mass (COM) to mean 3D hand speed relative to COM (Figueiredo, et al., 2011). Theoretically η_F with oar-motion can be measured by this method (Alexander, 2003), since η_F is the proportion of the \dot{W} required to move the oar ($\text{Speed}_{\text{oar}} \cdot \text{Force}_{\text{propulsive}}$) to \dot{W} required to move the body or the boat ($\text{Speed}_{\text{body}} \cdot \text{Force}_{\text{propulsive}}$), although it should be noted that human swimming motion consists of not only oar-like motion by the arms, but also kicking motion. Nevertheless, the contributions of the kicking actions are small and most of the propulsion is achieved by the arm (Deschodt et al., 1999), and no difference was found in η_F between swimming trials with and without kicking in front crawl in a study by Gourgoulis et al. (2014). Thus, the effect of the kicking on Froude efficiency was considered to be negligible.

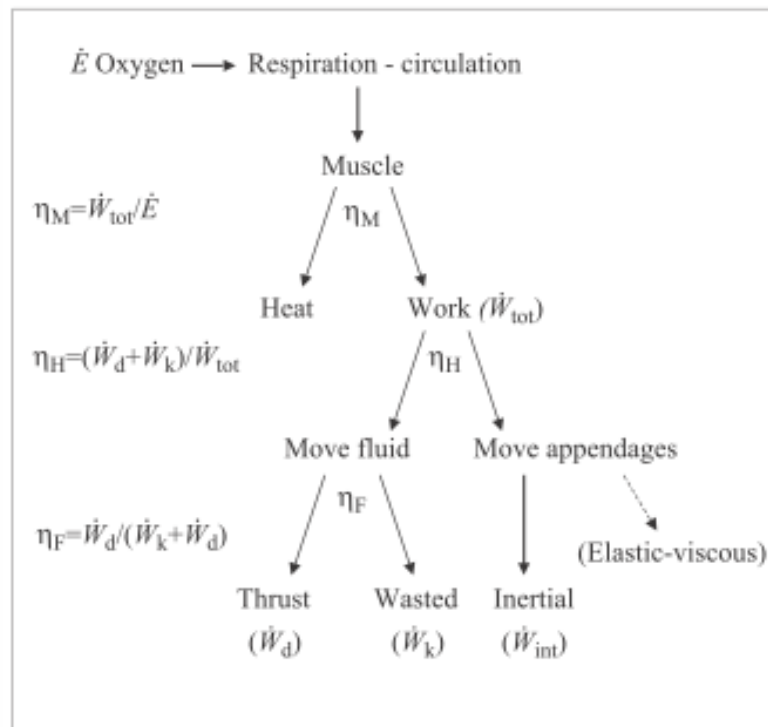


Figure 5. 1: Steps of energy conversion in aquatic locomotion (adapted from Zamparo et al., 2002).

Also, in previous studies, it was suggested that changes in velocity (intra-cycle velocity variation) of 10% in the swimming direction result in an additional work (\dot{W}_{tot}) demand of about 3%, which was calculated using a mathematical model (Nigg, 1983). This means intra-cycle velocity variation in the swimming direction (IVV_x) is a factor that affects the magnitude of \dot{E} . Barbosa, Lima, et al. (2006) reported positive correlations between \dot{E} in a given distance (energy cost: C) and IVV_x of $r=0.62$ ($p<0.01$) in front crawl, and $r=0.55$ ($p<0.01$) in back crawl. However, using the same calculation, Figueiredo, Barbosa, et al. (2012) showed opposite result in front crawl ($r=-0.34$, $p<0.05$). This was probably due to the use of different unit of C ($\text{J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$ in the study of Barbosa, Lima, et al., and $\text{kJ}\cdot\text{m}^{-1}$ in the study of Figueiredo, Barbosa, et al.). The use of C without being normalised by the body mass might have produced error in the result of Figueiredo, Barbosa, et al. (2012). On the other hand, the accuracy of the study of Barbosa, Lima, et al. (2006) is also questionable. In the study of Barbosa, Lima, et al. (2006), coefficient of variation (CV) of the COM speed during a stroke cycle was used to quantify the IVV_x during the stroke cycle, which suggested a possibility of underestimating IVV_x at fast swimming speeds (For detailed discussion regarding the calculation of IVV , see section 2.5.2.2). IVV calculated using CV can be useful for comparing IVV at the same speed, but it is not appropriate to discuss the change of IVV with the swimming speed using CV .

Nevertheless, the idea of positive correlations between the swimming speed and \dot{E} and/or C is logical since extra energy is required when the swimmer accelerates the body and the corresponding added mass, with the exception of a circumstantial reduction of the resistive force (Vilas-Boas et al., 2011)

As described above, it has been suggested that IVV_x is positively associated with energy expenditure. In this study, however, there was no significant difference in IVV_x between the strokes, although the mean value of IVV_x of the swimmers in back crawl was larger (15%) than that in front crawl with a medium effect size ($d=0.61$). However, the medium effect size might have produced by digitising error because the digitising error of IVV_x in this study was large (10.6% in front crawl, and 8.2% in back crawl). Considering that there were no differences in both IV_{max} and IV_{min} between front crawl and back crawl, it is logical that IVV_x is not different between front crawl and back crawl. Alves et al. (1996) reported that back crawl had higher IVV_x than front crawl at the speeds of 1.1, 1.2, and 1.3 $m \cdot s^{-1}$, whereas data in another study (Vilas-Boas et al., 2011) suggested smaller IVV_x in back crawl than in front crawl at the speed range of 1.3-1.5 $m \cdot s^{-1}$, although specific values of IVV_x in the two strokes were not reported in these studies. It is difficult to compare the results of the present study with these previous studies. Alves et al. (1996) did not specify the method used to calculate IVV_x . Therefore, it is possible that the calculation process in the present study and the study by Alves et al. (1996) were difference which produced the contradiction of the results in IVV_x . On the other hand, IVV_x in the study by Vilas-Boas et al. (2011) was based on CV of COM speed. Even though IVV calculation based on CV of COM speed has several limitations (see 2.5.2.2), the results in Vilas-Boas et al. (2011) is acceptable considering that swimmers showed smaller IVV_x in back crawl than in front crawl at the speed range of COM speed. However, it is still difficult to compare the results between the study by Vilas-Boas et al. (2011) and the present study, since the data in Vilas-Boas et al. (2011) in front crawl and back crawl was based on data of different groups of swimmers, whereas the result of the present study was based on the same group of swimmers. This study was the first study in which IVV_x in front crawl and back crawl of the same group of swimmers were investigated (except the study by Alves et al., in which the calculation process of IVV_x was unclear). In this study, swimmers did not show a significant difference in IVV_x between front crawl and

back crawl, and it can be concluded that the difference in \dot{E} between the strokes was not due to $IVVx$.

Differences in hand and foot kinematics between the strokes are possibly an explanation of the difference in the energy expenditure. Swimmers' foot path distance in back crawl was 26% longer than that in front crawl, which was due to 31% larger range of motion of the foot in the vertical-direction in back crawl. Since the foot path distance was different and the stroke cycle time was the same, the mean relative 3D foot speed in back crawl was 21% faster than that in front crawl. Although the work done and force applied on the water by the foot motion could not be measured, considering that the stroke cycle time was the same between the two strokes, faster 3D foot speed must have required swimmers to expend greater energy in back crawl than in front crawl, since faster 3D speeds would transfer larger kinetic energy to the water from the foot. In this study, however, foot kinematics were assessed using the 3D coordinates of the ankle, rather than the mid-point of the ankle and toe, due to the difficulty of identifying the position of the toe during the digitising process at times. This means that the effect of dorsal and plantar flexions on foot kinematics was ignored in this study. In future studies, it will be necessary to quantify foot kinematics during front crawl and back crawl using larger number of cameras or with additional devices such as inertial sensors.

Swimmers had similar duration and distance of the hand path relative to COM between the strokes during the propulsive phases (the pull and push phases). On the other hand, the hand path distance during the underwater non-propulsive phases (the entry and release phases) of swimmers in back crawl was 12% longer than that in front crawl, despite swimmers spending 11% less time in the underwater non-propulsive phases in back crawl than in front crawl. To achieve longer hand path distance relative to COM in a shorter time, swimmers had to achieve 20% faster mean 3D hand speed relative to COM in back crawl than in front crawl during the non-propulsive phases. Since there was no difference in the mean COM

speed, the faster 3D hand speed relative to COM caused the 9% lower η_F in back crawl than in front crawl (η_F was calculated as the ratio of the speed of COM to the mean 3D hand speed relative to COM in the stroke cycle).

Strictly speaking, it is preferable to compare η_P between the front crawl and back crawl to assess the difference of the efficiency between the strokes because η_F does not reflect the power used to move the body parts such as lower and upper limbs, however, it is currently difficult to investigate η_P because of technical limitations (see 2.4.2). Nevertheless, the primary factor to determine η_P is η_F (Zamparo et al., 2005) since η_P is multiplication of η_F and η_H (hydraulic efficiency which is the fraction of muscle work that moves fluid) according to Zamparo and Swaine (2012), and contribution of η_H on determining η_P is quite small compared with η_F (Zamparo et al., 2005). Also, the authors concluded that larger internal work (W_{int}) of the leg kick makes η_H smaller, while the contribution of W_{int} of the arm to η_H is rather small, which means the larger W_{int} of the leg kick, the smaller η_H , (and thus η_P). In this study, W_{int} of the leg in back crawl should be greater than that in front crawl, because swimmers' foot speeds were faster in back crawl, which reflected that swimmers move their legs more in the same cycle time in back crawl than in front crawl. This means that η_H in back crawl was probably smaller than that in front crawl. Thus, although η_P was not calculated in this study, considering the smaller η_F and the faster 3D foot speed (which suggested smaller η_H) in back crawl than in front crawl, η_P should be smaller in back crawl than in front crawl.

Since smaller η_F indirectly reflects smaller η_P , which suggests that greater energy would have been spent for work which does not contribute to propulsion, the smaller η_F (and probably η_P) in back crawl could be a reason of the higher energy expenditure in back crawl than in front crawl at the same swimming speed in this study.

It should be noted, however, the calculation of η_F was based on the assumption of constant COM and 3D hand speed, which is not the case in actual swimming. It means that the results of η_F in this study do not reflect the differences in hand acceleration and deceleration between front crawl and back crawl, which is a limitation of this study.

Although the resistive force could not be measured in this study, it is worth discussing the possible difference in the resistive force between front crawl and back crawl. The larger the resistive force, the greater work the swimmer has to do to maintain speed (Di Prampero et al., 1974) and therefore the smaller η_F and η_P (Toussaint and Hollander, 1994). Kinematic values which possibly affect resistive force are vertical displacements of the leg since it potentially increases the cross sectional area toward the swimming direction, and lateral movement of the body or/and body segments (E. Maglischo, 2003). These motions increase frontal cross sectional area, and dissipate kinetic energy to the water in the non-swimming directions. Thus, the possibility of the larger resistive force in back crawl than in front crawl is discussed in the next section 5.2.3.

5.2.3. The Possibility of the Difference in the Resistive Impulse and Force between Front Crawl and Back Crawl

It was reported that the wave drag is one of the major components of the total drag during swimming (Toussaint, 2002; Vennell et al., 2006). However, Toussaint (2002) investigated the percentage of total drag, and concluded that although wave drag was 21% of the total drag at the swimming speed of $1.9 \text{ m}\cdot\text{s}^{-1}$, it was negligible below swimming speeds of $1.7 \text{ m}\cdot\text{s}^{-1}$. In this study, the testing speed was approximately $1.0 \text{ m}\cdot\text{s}^{-1}$. Thus it was assumed the effect of the wave drag in this study was negligible.

Although the resistive force could not be calculated in this study, it is possible to compare the influence of the drag on the energy expenditure in front crawl and back crawl using the hand speed and acceleration and the net impulse. According to Sanders (1999), the force (F) acting on swimmer's hand can be estimated using the equation below

$$F = \frac{(C_x \rho A |v|^2)}{2} + \frac{(C_y \rho A |v|^2)}{2} + \frac{(C_z \rho A |v|^2)}{2} + m_x |a_x| + m_y |a_y| + m_z |a_z|$$

Equation 5. 1: The force acting on swimmer's hand, where C_x , C_y , C_z are the coefficients for the component forces in the x, y, and z directions; A is the surface area of the hand; ρ is the density of the water | v | is the speed of the hand relative to the water; m_x , m_y and m_z is the mass of water given and mean acceleration in the x, y, and z directions by the hand (| a_x |, | a_y | and | a_z |).

Although there are several other fluid dynamical factors that affects the propulsive force produced by the hand, such as the vortex shedding effect (Pai and Hay, 1988), this equation suggests that the hand speed and acceleration are factors which determine a part of the propulsive force produced by the hand. In fact, Kudo et al. (2012) showed the propulsive forces by the hand (which was measured by total of twelve pressure sensors) during front crawl to be increased in proportion to the square of the hand velocity ($R^2=0.93-0.97$ for propulsive drag force, and $R^2=0.65-0.96$ for propulsive lift force). Also Kudo et al. (2013) measured the effect of hand acceleration on the propulsive force produced by the hand using a robotic hand model and a tri-axial load cell, and concluded that the hand acceleration created up to 3.8 times larger propulsive force on the hand than a non-accelerating hand. Also the authors reported that even hand deceleration created larger propulsive drag on the hand than a non-accelerating/decelerating hand, and thus hand acceleration and deceleration value (in other words, absolute value of hand acceleration) are important factors which contribute to swimmer's propulsive force production.

In this study, there were no differences in hand speeds in swimming direction during the pull and push phases (which contribute to create propulsive drag forces). However, p-values were close to the significant level and the effect sizes were large (pull phase: $p=0.11$, $d=0.78$. push phase: $p=0.07$, $d=1.18$). Swimmers had significant larger hand acceleration and deceleration in the swimming direction in back crawl than in front crawl (76% larger in the pull phase, $p<0.01$, $d=2.8$. 43% larger in the push phase, $p<0.01$, $d=1.51$). Swimmers also had a significantly fast hand speed during the underwater phases (the entry, pull, push and release phases) in the lateral direction (which contributes to produce propulsive lift forces) in back crawl than in front crawl by 56%. Therefore, swimmer's hands may have produced larger propulsive impulse on the water in back crawl than in front crawl during the stroke cycle considering that the duration of the propulsive phases was the same between the strokes, and the difference in the underwater phases between the strokes was only 12%. Given that swimmers had the same swimming speed in both strokes and there were no differences in net impulses (obtained by COM acceleration and the swimmer's mass) during the pull and push phases between the two strokes (back crawl: 10.28 N·s vs front crawl: 11.08 N·s), it is logical to conclude that the resistive impulses during the pull and push phases were larger in back crawl than in front crawl. This conclusion is, however, based on two assumptions. The first assumption is that the propulsion by the legs during the propulsive phases was not greater in front crawl than back crawl. This assumption is reasonable given that the speed of foot motion during the kick was actually greater in back crawl than front crawl. Also, there is no evidence to suggest that kicking contributes strongly to propulsion (Deschodt et al., 1999; Yanai, 2001) and it is estimated to contribute only from 9 to 13 % (Gourgoulis et al., 2014; Özçaldıran & Özkol, 2009) in front crawl and 9.8% in back crawl (Özçaldıran and Özkol, 2009). The second assumption is that the swimmers oriented their hands to optimise the forces produced in the swimming direction. This assumption could not be verified in this study since hydrodynamic force was not investigated, and thus, this was a limitation of this study. In future studies, it is necessary to investigate the difference in hydrodynamic forces

during underwater stroke phases between front crawl and back crawl. It should also be noted that the reliability error in net impulse was large, and thus, there is a possibility that the non-significant difference was possibly due to the digitising error.

In this study, swimmers had lower mean vertical displacement (deeper position relative to the water surface) of the foot (44%), even though there were no differences in vertical displacements of mid-hip and knee. The deeper position of the foot possibly created larger frontal cross sectional area on y-z plane in back crawl, which might have created larger form drag in back crawl than in front crawl (Figure 5.2).

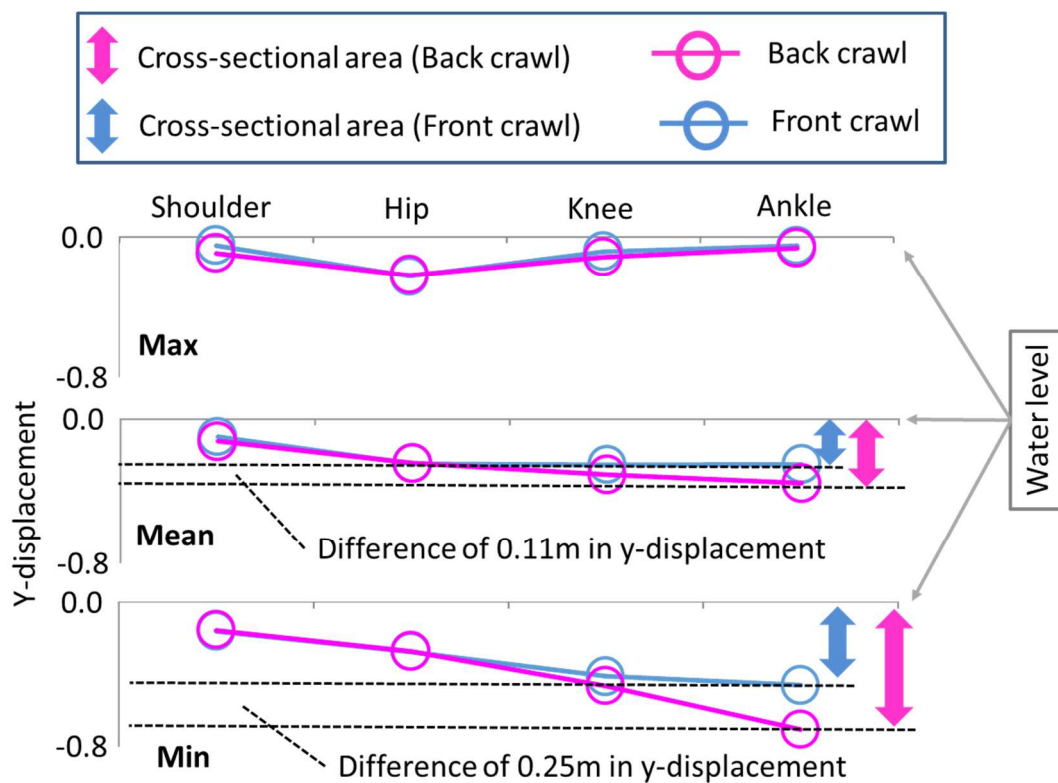


Figure 5. 2: The maximum, mean and minimum vertical displacement (Y-displacement) of shoulder, hip, knee and foot throughout the stroke cycle in front crawl and back crawl.

In addition to the orientation of the body and limbs in the vertical plane, the orientation in the horizontal plane also affects resistance. In this study, yaw angle of the swimmer during front crawl and back crawl was calculated as the angle between the middle shoulder – middle hip vector projected onto the x-z plane and the x-axis. Although there was no significant difference, swimmers tended to show 28% larger yaw angle fluctuation (the difference of the maximum and minimum yaw angles) in back crawl than in front crawl, with a large effect size ($p=0.11$, $d=0.83$). The tendency of larger yaw angle in back crawl than in front crawl might have been due to the magnitude and the timing of the maximum lateral distance between the hand and COM ($Z_{\max}\text{-Distance}_{\text{Hand-COM}}$) during the pull and push phases of the stroke as this distance provides a moment arm for forces to produce the yaw. Swimmers had larger $Z_{\max}\text{-Distance}_{\text{Hand-COM}}$ (31% larger in left hand, and 47% larger in right hand) in back crawl than in front crawl. Also, swimmers achieved $Z_{\max}\text{-Distance}_{\text{Hand-COM}}$ during the propulsive phases (the pull and push phases) in back crawl (Figure 5.4), but during the above-water phase in front crawl (Figure 5.3). It is logical that the forces swimmers applied on the water with a large moment arm during the propulsive phases produced a large yaw in back crawl. Conversely, the effect of the moment arm on yaw was small in front crawl since it was in the above-water phase where swimmers had the largest $Z_{\max}\text{-Distance}_{\text{Hand-COM}}$. Therefore, the yaw angle fluctuation in back crawl possibly produced larger resistive forces in back crawl than in front crawl. Figure 5.5 and Figure 5.6 show $Z_{\max}\text{-Distance}_{\text{Hand-COM}}$ and yaw angle during a stroke cycle of a swimmer in front crawl and back crawl respectively, as examples of the relationship between $Z_{\max}\text{-Distance}_{\text{Hand-COM}}$ and yaw angle to support this argument. In both strokes, the swimmer changed yaw angle during the lateral stroke movement toward the body. This phenomenon suggested that the swimmer had larger yaw angle fluctuation in back crawl than in front crawl because the swimmer had greater lateral stroke movement, in other words, larger $Z_{\max}\text{-Distance}_{\text{Hand-COM}}$. It should be reminded, however, the difference in the yaw angle fluctuation between the strokes was not significant. Therefore, the above argument might be applicable only for swimmers who have technical

characteristics showed in Figure 5.5 and Figure 5.6, and this argument cannot be generalised.

In fact, not all swimmers in this study showed this technical characteristics.

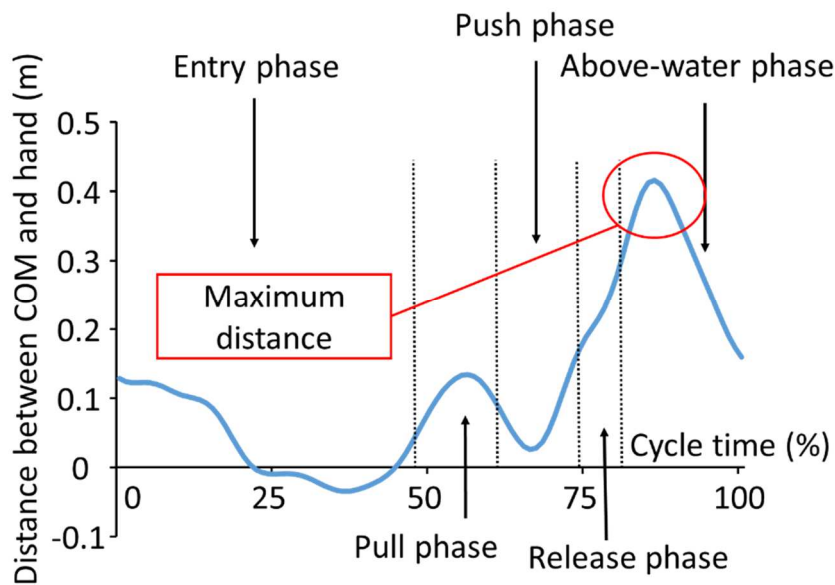


Figure 5. 3: Lateral distance between COM and hand (wrist) in front crawl.

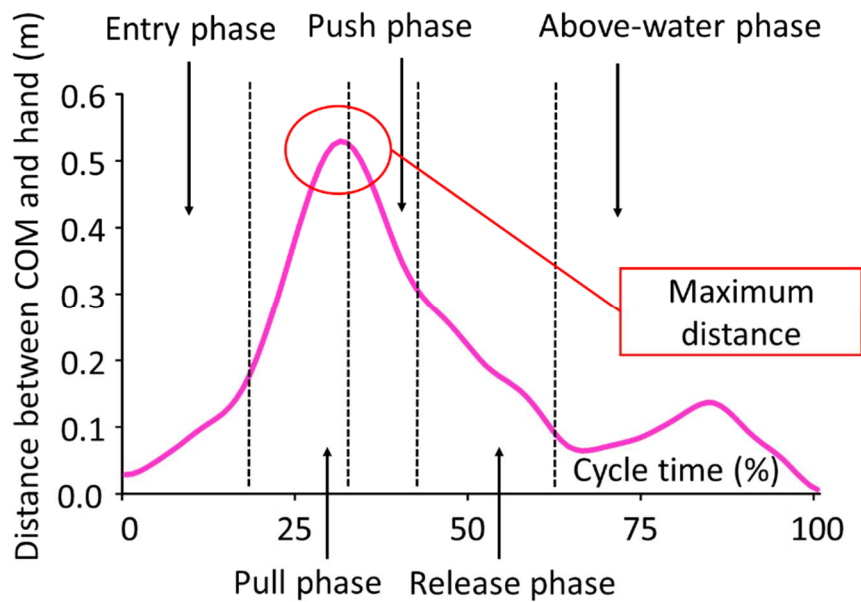


Figure 5. 4: Lateral distance between COM and hand (wrist) in back crawl.

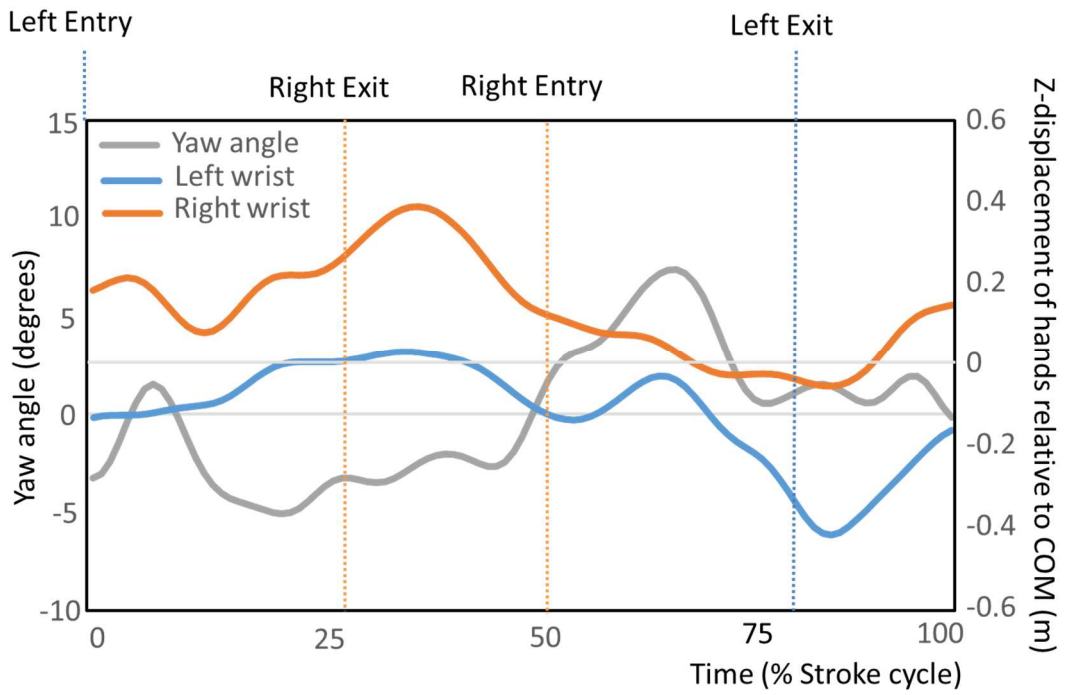


Figure 5. 5: Yaw angle and lateral displacement of hands relative to COM in front crawl.

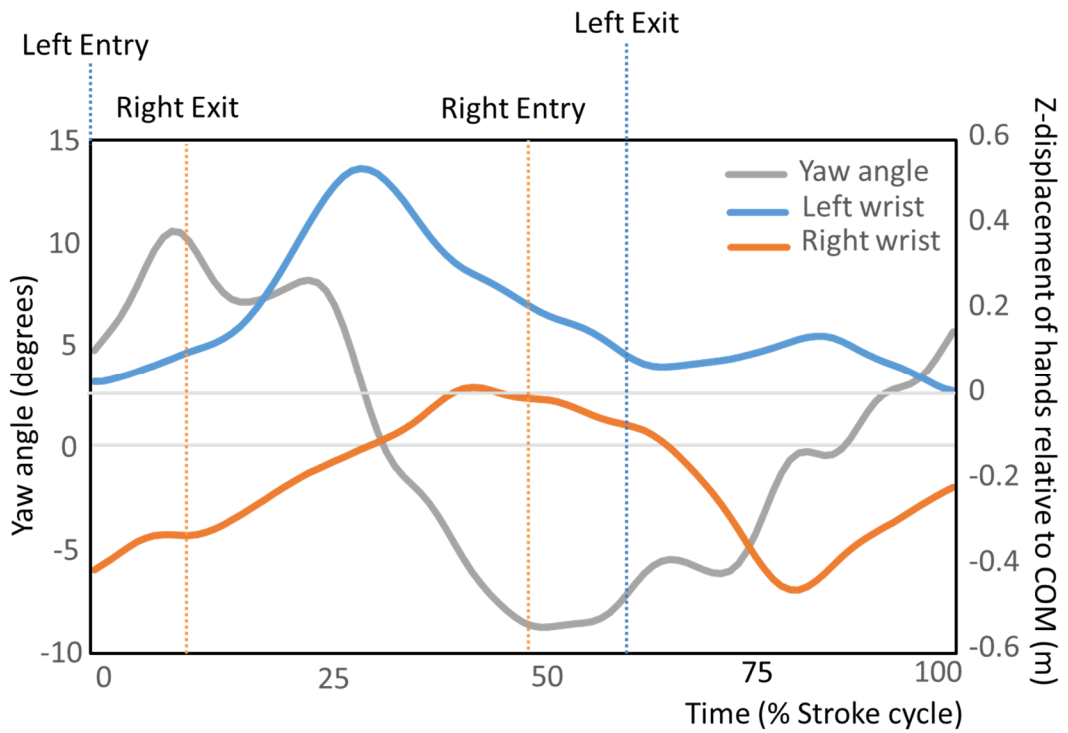


Figure 5. 6: Yaw angle and lateral displacement of hands relative to COM in back crawl.

Another explanation for the larger lateral hand movement in back crawl than in front crawl is smaller body roll angle in back crawl (maximum shoulder roll: 35% smaller, maximum hip roll: 60% smaller). According to Maglischo (2003), body roll contributes to the swimmer placing the arm in a better position during the pull, so that the swimmer can minimise lateral movements of the body, in both front crawl and back crawl. Prins (2007) also stated that a primary objective of body roll is to place the arm close to the long axis of the body so that the lateral motions of the trunk and leg are minimised. Payton et al. (1999) suggested that the body roll does not contribute to the medial hand motion in front crawl since the swimmer starts rolling back during the downsweep phase, or the beginning of insweep phase. However, it is still possible that body roll angle affects the medial-lateral hand position of the hand since the larger roll angle makes the lateral distance between shoulder joint (as well as the arm and the hand) and the midline of the body shorter (Figure 5.7), and it is logical to assume that the shoulder roll angle also contributes to the lateral distance between the hand and the centre of mass to some extent.

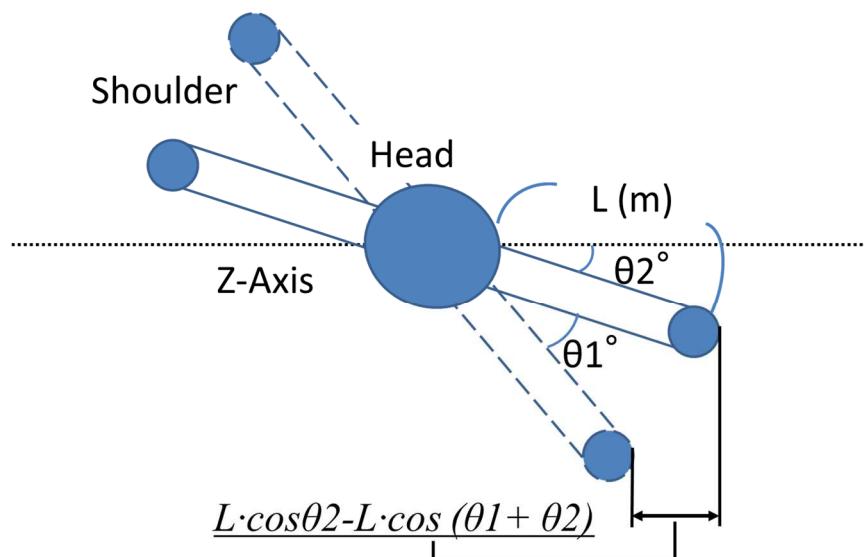


Figure 5. 7: The relationship between shoulder roll angle and the lateral shoulder displacement.

5.2.4. Summary of Study 1

The first purpose of the study 1 was to quantify both physiological and biomechanical differences at an aerobic exercise intensity to assess whether front crawl is more economical than back crawl at this intensity. To do so, the difference in the energy expenditure between front crawl and back crawl at the same selected speed below the anaerobic threshold and the differences in kinematics between the strokes which affect the difference in the energy expenditure were investigated.

Although there were no differences in stroke parameters between front crawl and back crawl at the same speed below the anaerobic threshold, front crawl was more economical than back crawl because Froude efficiency was higher in front crawl than that in back crawl.

Greater kicking speed and range of motion in back crawl than in front crawl might have required the swimmers to spend greater energy in back crawl, because the larger foot speed and range of motion would require larger internal work for the equivalent useful mechanical energy, which is associated with the efficiency.

Although the resistive impulse during the stroke cycle could not be measured in this study, the deeper foot position in the water (vertical displacement of the foot) in back crawl might have created larger frontal cross-sectional area which caused to produce larger resistive forces than in front crawl. The difference in the lateral position of the hand in relation to the centre of mass possibly possibly caused larger lateral movement in back crawl than in front crawl, which produced slightly larger yaw angle fluctuation in back crawl than in front crawl for some participants.

5.3. Study 2 and Study 3: What Are the Kinematic Differences between Front Crawl and Back Crawl above the Anaerobic Threshold?

In Study 1, the difference of the energy expenditure and the kinematics between front crawl and back crawl below the anaerobic threshold were measured and discussed. In study 2 and Study 3, kinematics of the two strokes above the anaerobic threshold were measured, although the energy expenditure above the anaerobic threshold could not be assessed because of the unreliability of assessing anaerobic energy expenditure during swimming (Thevelein et al., 1984). In the following sections, the differences in kinematics between the two strokes above the anaerobic threshold at the same selected speed (trial-1: $1.30 \pm 0.06 \text{ m}\cdot\text{s}^{-1}$, trial-2: $1.40 \pm 0.07 \text{ m}\cdot\text{s}^{-1}$, trial-3: $1.49 \pm 0.07 \text{ m}\cdot\text{s}^{-1}$, trial-4: $1.58 \pm 0.08 \text{ m}\cdot\text{s}^{-1}$) and the same selected intensity (trial-1: BC $1.30 \pm 0.06 \text{ m}\cdot\text{s}^{-1}$, FC $1.44 \pm 0.06 \text{ m}\cdot\text{s}^{-1}$, trial-2: BC $1.40 \pm 0.07 \text{ m}\cdot\text{s}^{-1}$, FC $1.55 \pm 0.07 \text{ m}\cdot\text{s}^{-1}$, trial-3: BC $1.49 \pm 0.07 \text{ m}\cdot\text{s}^{-1}$, FC $1.65 \pm 0.07 \text{ m}\cdot\text{s}^{-1}$, trial-4: BC $1.58 \pm 0.08 \text{ m}\cdot\text{s}^{-1}$, FC $1.75 \pm 0.08 \text{ m}\cdot\text{s}^{-1}$) are discussed.

5.3.1. Discussion – Study 2: Kinematic Differences between Front Crawl and Back Crawl at the Same Selected Speeds above the Anaerobic Threshold.

5.3.1.1. Is Front Crawl More Efficient than Back Crawl at the Same Selected Speeds above the Anaerobic Threshold?

Froude efficiency (the proportion of the power swimmers used for the propulsion to the whole power swimmers applied on the water), which was calculated as the proportion of the mean centre of mass speed and mean 3D under water hand speed relative to the centre of mass (Figueiredo, Toussaint, et al., 2013) in front crawl was significantly higher than that in back crawl at all trials (trial-1: 0.70 vs 0.56, trial-2: 0.68 vs 0.55, trial-3: 0.66 vs 0.52, trial-4: 0.59 vs 0.48). These results suggest the higher swimming efficiency in front crawl than in

back crawl (for detailed explanation for the relationship between Froude efficiency and swimming efficiency, see Discussion Section 5.1.2).

Also, the swimmers had significantly larger stroke index ($\text{m}^2 \cdot \text{cycle}^{-1} \cdot \text{s}^{-1}$) in front crawl than in back crawl in all trials (trial-1: 3.37 vs 3.08, trial-2: 3.64 vs 3.28, trial-3: 3.68 vs 3.21, trial-4: 3.46 vs 3.19). These results also suggest the possibility of higher efficiency in front crawl than in back crawl at the same speed above the anaerobic threshold, since larger stroke index could indirectly reflect higher efficiency during swimming under the assumption that the longer stroke length represents better efficiency at a given swimming speed (Costill et al., 1985). This assumption was supported by Longo et al. (2008) who reported a positive correlation between stroke index and Froude efficiency in front crawl ($r=0.74$, $p<0.01$). A study by Fernandes, Marinho, et al. (2006) who investigated the duration swimmers could maintain their $\dot{V}_{\text{O}_2 \text{ max}}$ speed ($\text{TLim}-v\dot{V}_{\text{O}_2 \text{ max}}$) also indirectly supported this assumption. In their study, significant positive correlations between stroke length and $\text{TLim}-v\dot{V}_{\text{O}_2 \text{ max}}$ ($r=0.52$, $p<0.01$), and between stroke index and $\text{TLim}-v\dot{V}_{\text{O}_2 \text{ max}}$ ($r=0.45$, $p<0.05$) were reported, indicating that higher stroke length and index led lower energy cost, because the lower the energy cost, the longer the swimmer sustains the swimming speed (Fernandes, Billat, et al., 2006). Since the efficiency is inversely proportional to the energy cost (Figueiredo, Zamparo, et al., 2011; Zamparo, 2006; Zamparo, Pendergast, et al., 2005), it is logical that long stroke length and high stroke index indirectly reflects high swimming efficiency at a given speed.

Another possible factor which suggested larger efficiency in front crawl than in back crawl was the difference in body roll angle. In front crawl, there was a significant main effect of swimming speed on shoulder and hip roll angles. This result was logical considering the positive relationship between body roll angle and SF proposed by Yanai (2003). However, there was no main effect of swimming speed on body roll angle in back crawl, suggesting that even though swimmers increased their speed (consequently, SF), swimmers did not (or

could not) change their body roll angle. This means that swimmers should increase shoulder and hip roll angular velocity greater in back crawl than in front crawl to increase their *SF* and swimming speed for a given amount, which probably requires swimmers to spend greater energy to roll their shoulder and hip. To spend extra energy for non-propulsive movement (i.e. roll the shoulder and hip) indirectly suggested lower efficiency in back crawl than in front crawl.

5.3.1.2. Why Is Front Crawl More Efficient than Back Crawl at the Same Selected Speeds above the Anaerobic Threshold?

5.3.1.2.1. Why Is Stroke Index Larger in Front Crawl than in Back Crawl?

Since the swimming speeds at the four trials were the same, the differences in the stroke index were clearly caused by the difference in stroke length. Stroke length in back crawl was significantly shorter than that in front crawl at trial-2 (2.66 m·cycle⁻¹ vs 2.44 m·cycle⁻¹), trial-3 (2.55 m·cycle⁻¹ vs 2.28 m·cycle⁻¹), and trial-4 (2.21 m·cycle⁻¹ vs 2.07 m·cycle⁻¹). In trial-1, the stroke length of the swimmers in front crawl was also longer than that in back crawl (2.63 m·cycle⁻¹ vs 2.48 m·cycle⁻¹) with a nearly large effect size ($d=0.71$), but the difference was not significant.

According to Hay (1993), swimmers generally need to increase the time over which they apply forces on the water to increase their stroke length. In this study, swimmers had longer propulsive phase duration (seconds) in front crawl than in back crawl (trial-1: 0.53 vs 0.49, trial-2: 0.53 vs 0.46, trial-3: 0.50 vs 0.44, trial-4: 0.45 vs 0.42), which was due to the longer push phase duration (seconds) in front crawl than in back crawl (trial-1: 0.28 vs 0.25, trial-2: 0.30 vs 0.24, trial-3: 0.28 vs 0.23, trial-4: 0.25 vs 0.22). Thus, the longer stroke length in

front crawl than in back crawl was due to the longer duration of the propulsive phases (pull and push phases) in front crawl. It should be noted that the definition of the propulsive phases in this study was where the swimmer conducted the backward motion of the wrist (i.e. where the swimmer conducted a propulsive motion of the hand to produce the propulsive drag force), and the phases where the swimmer potentially produced the propulsive lift force (which was whole underwater phases) was not considered. This phase definition was based on that the primary source of the resultant propulsive force was propulsive drag force (See 2.5.1.1). Yet, it was a limitation of this study that the propulsive phase in which the propulsive force produced by the swimmer actually exceeded the resistive force could not be quantified.

Hay (1993) also suggested that stroke length was determined by the forces exerted on swimmers during the stroke cycle – namely the propulsive force and the resistive force (Figure 5.8). In other words, the shorter stroke length in back crawl than in front crawl was probably due to either smaller propulsive impulse or larger resistive impulse during the stroke cycle in back crawl. Although both the propulsive and resistive forces could not be measured in this study, it is possible to discuss the possible differences in these forces between front crawl and back crawl using several kinematic variables.

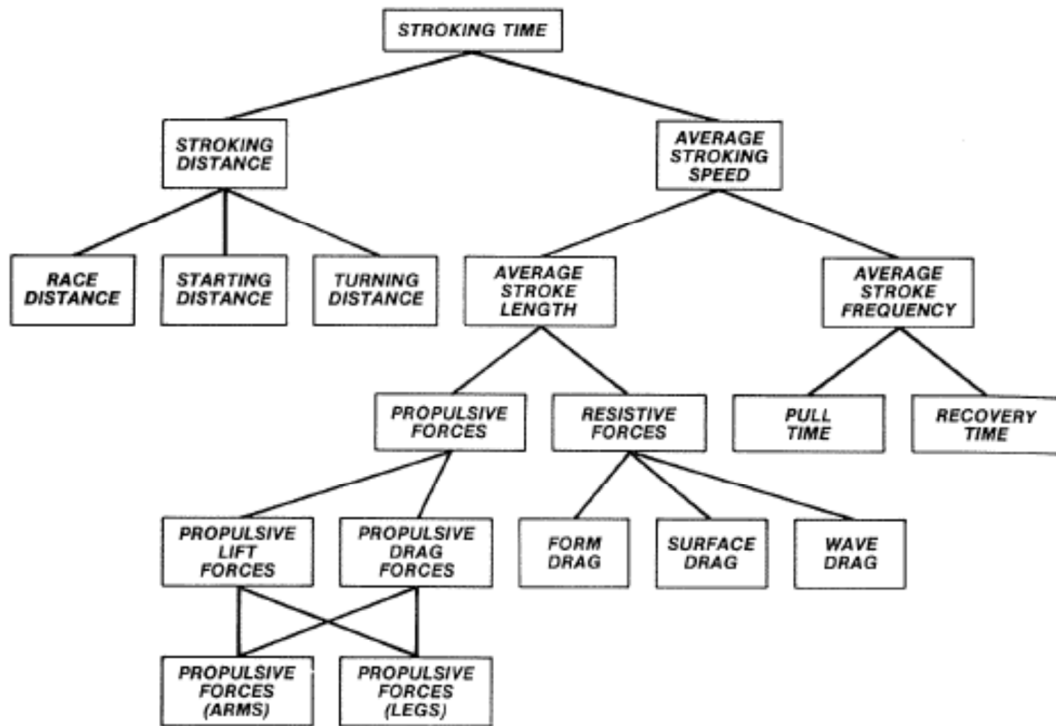


Figure 5. 8: Basic factors that determine stroke time (adapted from Hay, 1993).

As being discussed in Section 5.2.3., hand speed and acceleration in swimming direction can be indicators of the propulsive force produced by the hand. According to Kudo et al. (2012; 2013), the propulsive force generated by the hand increased as the hand speed, acceleration and deceleration increased. In this study, there were no differences in the hand speed during the pull phase between front crawl and back crawl. However, the hand speed ($\text{m}\cdot\text{s}^{-1}$) during the push phase in back crawl was significantly faster than that in front crawl (trial-1: 1.37 vs 1.14, trial-2: 1.37 vs 1.16, trial-3: 1.44 vs 1.17, trial-4: 1.43 vs 1.21). Also swimmers had larger hand acceleration ($\text{m}\cdot\text{s}^{-2}$) in the pull phase (trial-1: 8.61 vs 5.94, trial-2: 9.22 vs 6.73, trial-3: 9.80 vs 7.60, trial-4: 10.75 vs 7.38) and larger hand deceleration ($\text{m}\cdot\text{s}^{-2}$) in the push phase (trial-1: -7.21 vs -5.25, trial-2: -7.74 vs -5.57, trial-3: -8.69 vs -6.33, trial-4: -9.85 vs -

6.49) in back crawl than in front crawl. Swimmers also had larger hand speed ($\text{m}\cdot\text{s}^{-1}$) in the lateral direction in back crawl than in front crawl at all trials (trial-1: 0.73 vs 0.37, trial-2: 0.78 vs -0.43, trial-3: 0.87 vs 0.46, trial-4: 0.98 vs 0.55). Thus, swimmers probably applied larger mean propulsive drag force during the pull and push phases, and larger mean propulsive lift force during the underwater phases in back crawl than in front crawl.

Although swimmers had 1.12-1.25 times longer push phase duration (trial-1: 1.12 times, trial-2: 1.25 times, trial-3: 1.22 times, trial-4: 1.14 times) in front crawl than in back crawl, the square of the mean hand speed in swimming direction during the push phase in back crawl was 1.39-1.51 times larger (trial-1: 1.45 times, trial-2: 1.39 times, trial-3: 1.51 times, trial-4: 1.40 times) than that in front crawl. The square of the mean hand speed in the lateral direction were 1.43-1.75 times larger in back crawl than in front crawl (trial-1: 1.44 times, trial-2: 1.43 times, trial-3: 1.66 times, trial-4: 1.75 times) whereas the duration of the underwater phases in front crawl was only 1.15-1.24 times longer than that in back crawl (trial-1: 1.24 times, trial-2: 1.23 times, trial-3: 1.24 times, trial-4: 1.15 times). Thus, assuming that the coefficients of the forces were the same between the two strokes, the propulsive impulse must have been larger in back crawl than in front crawl.

However, as previously noted, swimmers had longer stroke length in front crawl than in back crawl despite the possibility of the larger propulsive impulse in back crawl. These results suggest that swimmers probably had larger resistive impulse in back crawl than in front crawl during the stroke cycle, since stroke length is determined by the balance between the propulsive impulse and the resistive impulse during the stroke cycle (Hay, 1993). It should be reminded that this conclusion is based on two assumptions – namely the assumption of the propulsion by the legs being not greater in front crawl than in back crawl, and appropriate hand orientation assumption to optimise the forces produced in the swimming direction in both strokes. As being discussed in the section 5.2.3, the first assumption is reasonable. On the other hand, the second assumption could not be verified in this study due

to the lack of fluid forces data. Thus, there is a possibility that the faster hand speed in the swimming and lateral direction having been simply due to that the hand slipping the water in back crawl more than in front crawl. In the future, it will be necessary to investigate the fluid forces acting on the hand during front crawl and back crawl.

According to Barbosa et al. (2013), intra-cycle velocity variation in swimming direction (IVV_x) is caused by the balance between propulsive and resistive forces, and has a strong positive correlation with the mean resistive force during the stroke ($r=0.72$, $p=0.03$). This correlation means large IVV_x might reflect large mean resistive force during the stroke cycle. Although it is difficult to assess resistive and propulsive forces accurately in swimming, and thus, direct relationships between the resistive force, IVV_x , and stroke length have not yet been quantified, it is logical that sudden increase of body resistive force would decrease minimum speed during the stroke cycle (and thus to increase of IVV_x), which negatively affects stroke length.

In this study, IVV_x ($m \cdot s^{-1}$) in back crawl was significantly larger than that in front crawl in trial-3 (0.33 vs 0.42) and trial-4 (0.39 vs 0.46). In trial-2, the mean value of IVV_x in back crawl was larger than that in front crawl (0.40 vs 0.34) with a medium effect size ($d=0.58$), although the difference did not reach significance at $p<0.05$ ($p=0.11$). There were no differences in intra-cycle maximum velocity (IV_{max} : $m \cdot s^{-1}$) in all trials, whereas intra-cycle minimum velocity (IV_{min} : $m \cdot s^{-1}$) in front crawl was significantly faster than that in back crawl in trial-2 (1.21 vs 1.15, $p<0.05$), trial-3 (1.28 vs 1.20, $p<0.01$), and trial-4 (1.41 vs 1.30, $p<0.05$). Thus, the significant differences in IVV_x at trial-3 and 4, and the tendency of larger IVV_x in back crawl than in front crawl were caused by the differences in IV_{min} .

In this study, the mean and minimum displacements of the foot in vertical-direction in back crawl were deeper in the water relative to the water surface than that in front crawl (trial-1: -0.21 vs -0.32, trial-2: -0.21 vs -0.31, trial-3: -0.21 vs -0.31, trial-4: -0.19 vs -0.30) whereas

there were no differences in the knee displacements. It is possible the foot position affects swimmers IV_{min} since the deeper foot position potentially creates larger frontal cross sectional area, and thus swimmer's form drag.

Considering that the velocity fluctuation is caused by the balance between propulsive and resistive forces, and thus minimum velocity is caused by resistive force (Barbosa et al., 2013), it is possible that the difference in IV_{min} in trial-2, trial-3, and trial-4 suggested the swimmers had larger resistive force in back crawl than in front crawl (assuming that the swimmer produced larger mean propulsive force during the stroke cycle in front crawl, which was supported by the faster hand speed in back crawl). Thus, the longer stroke length in front crawl than in back crawl in trial-2, trial-3 and trial-4 could be explained by the faster IV_{min} (and smaller $IVVx$), which indirectly reflects smaller resistive force.

In summary, swimmers had larger stroke index in front crawl than in back crawl, because stroke length in front crawl was slightly longer than that in back crawl. Swimmers probably produced larger mean propulsive forces by the hand in back crawl than in front crawl which was assumed from larger mean hand speeds, acceleration, and deceleration. However, swimmers could still have longer stroke length in front crawl than in back crawl because of longer duration of the propulsive phases, and possibly smaller resistive forces in front crawl which was explained by larger IV_{min} (and smaller $IVVx$) in front crawl. Although there was no difference in IV_{min} and $IVVx$ between front crawl and back crawl in trial-1, swimmers had larger stroke length in front crawl than in back crawl because of longer duration of the propulsive phases.

Swimmers had larger yaw angle fluctuation in back crawl than in front crawl at trial-1. This was probably due to the larger maximum distance between hand and COM in lateral direction, as discussed in Study 1 (see 5.1.3). However, IV_{min} at trial-1 in front crawl and back crawl were not significantly different, and there were no significant differences in yaw

angle fluctuation between front crawl and back crawl at trial-2, trial-3, and trial-4 (where the differences in IV_{min} between the strokes were significant). Thus, the effect of yaw angle fluctuation difference on the difference IV_{min} (and thus, resistive force) was probably small.

5.3.1.2.2. Why Is Froude Efficiency Higher in Front Crawl than in Back Crawl?

According to Figueiredo et al. (2011), η_F can be calculated as the proportion of the mean centre of mass speed and mean 3D hand speed relative to the centre of mass during the stroke cycle. Since there were no differences in the centre of mass speed in all trials, the difference in η_F was due to the faster mean 3D hand speed ($3Du_{SC}$: $\text{m}\cdot\text{s}^{-1}$) relative to the centre of mass during the stroke cycle in back crawl than in front crawl (trial-1: 1.83 vs 2.23, trial-2: 2.04 vs 2.45, trial-3: 2.23 vs 2.73, trial-4: 2.69 vs 3.20).

In this study, the product of the mean $3Du_{SC}$ in each phase and the relative duration of the phase (contribution factor: $\frac{3Du_{phase} \cdot t_{phase}}{t_{SC}}$) was compared between front crawl and back crawl since the contribution factor during the phases determine $3Du_{SC}$ (Figure 5.9).

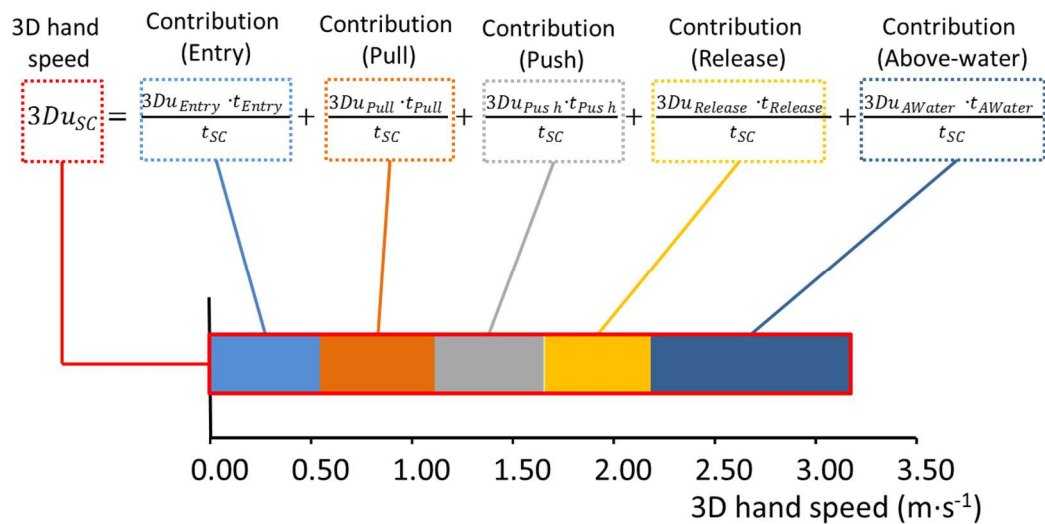


Figure 5. 9: Contribution of each phase on determining the 3D hand speed.

One of the phases which had larger contribution factor in back crawl than in front crawl was the release phase. This means that although the mean 3D hand speed during the release phase ($3Du_{Release}$) in back crawl was slower than that in front crawl (trial-1: 2.38 vs 1.44, trial-2: 2.66 vs 1.58, trial-3: 3.59 vs 1.86, trial-4: 3.16 vs 2.34), the release phase still contributed to the faster mean 3D hand speed during the stroke cycle. This was due to the longer duration of the release phase in relation to the stroke cycle ($\frac{t_{Release}}{t_{sc}}$) in back crawl than in front crawl (trial-1: 0.22 vs 0.06, trial-2: 0.22 vs 0.06, trial-3: 0.20 vs 0.05, trial-4: 0.20 vs 0.06). The longer relative duration of the release phase in back crawl than in front crawl was probably due to that a second down-sweep in the back crawl occurs after the hand stopped moving backwards with respect to the water (Figure 5.11), whereas the release phase of front crawl only consisted of the up-sweep motion (Figure 5.10).

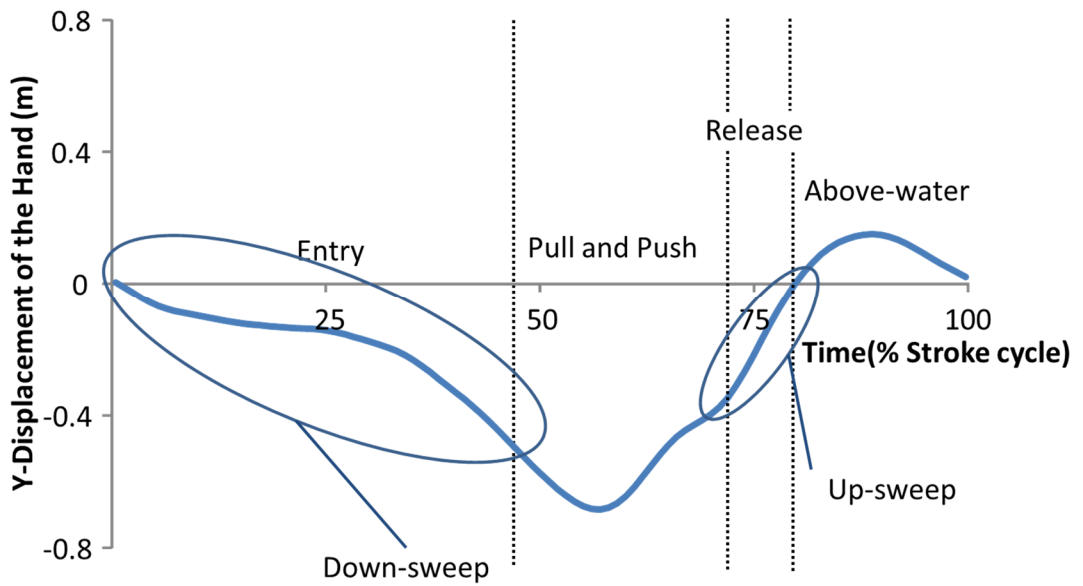


Figure 5. 10: Down-sweep and up-sweep motion during front crawl.

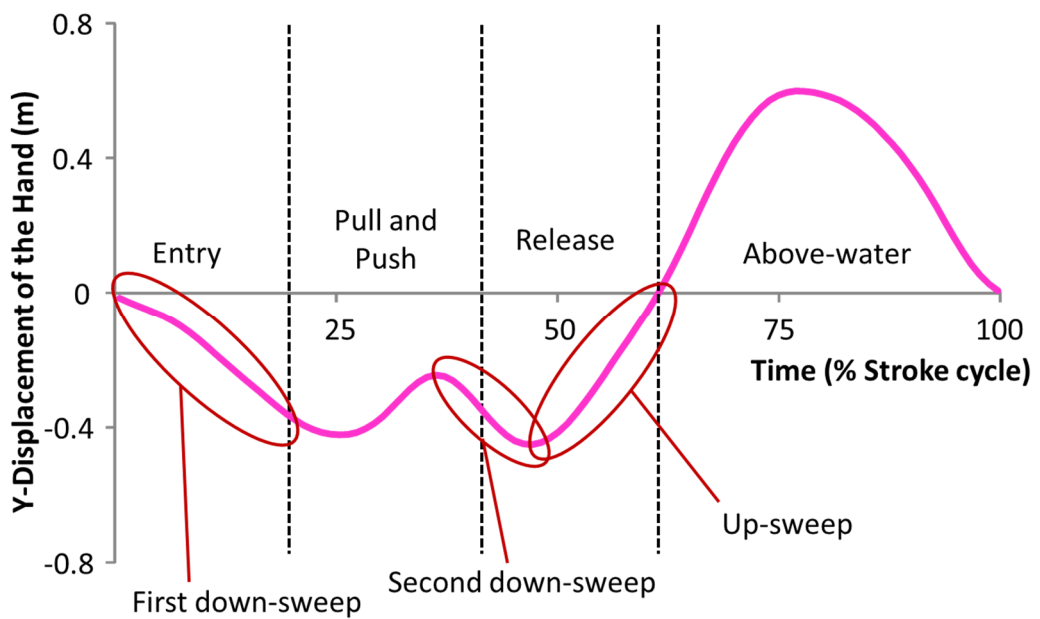


Figure 5. 11: Down-sweep and up-sweep motion during back crawl.

Another phase which had larger contribution factor in back crawl than in front crawl was the pull phase. Since there was no difference in the duration of the pull phase between the strokes, the larger contribution factor of the pull phase on determining the mean 3D hand speed in back crawl was due to the faster mean 3D hand speed relative to the centre of mass during the pull phase in back crawl than in front crawl (trial-1: 2.68 vs 2.80, trial-2: 2.80 vs 2.93, trial-3: 2.77 vs 3.75, trial-4: 3.62 vs 4.07).

The above-water phase also had a larger contribution factor in back crawl than in front crawl. This was due to the longer duration of the phase in back crawl than in front crawl since there were no differences in the 3D hand speed during the above-water phase at any trials except trial-4 (nevertheless, the effect size of the difference at trial-4 was small) . The longer duration of the above-water phase in back crawl than in front crawl was due to the longer hand path distance (m) during the phase in back crawl than in front crawl (trial-1: 1.96 vs 1.51, trial-2: 2.00 vs 1.55, trial-3: 2.00 vs 1.54).

To summarise, Froude efficiency was lower in back crawl than in front crawl because the mean 3D hand speed relative to the centre of mass during the stroke cycle in back crawl was faster than that in front crawl. This was due to the longer duration of the release and above-water phases, caused the longer hand path distance during the phases), and the faster mean 3D hand speed relative to the centre of mass during the pull phase in back crawl than in front crawl.

According to Toussaint et al. (1988, 1990) and Zamparo et al. (2011), Froude efficiency is calculated by the equation below (Equation 5.2).

$$\eta_F = P_D \cdot P_O^{-1}$$

Equation 5. 2: The relationship between Froude efficiency (η_F), total mechanical power delivered by the swimmer (P_O) and the power used to overcome the resistive force (P_D)

This equation suggests that if the swimmer has to spend much energy to overcome the drag (in other words, if the swimmer has large resistive forces), Froude efficiency becomes small. Although resistive force during front crawl and back crawl could not be assessed in this study, it is still possible to discuss possible difference in resistive force between the strokes using several kinematic variables, which could indirectly explain larger resistive force in back crawl than in front crawl.

As described in Section 5.3.1.2.1, Swimmers had larger mean hand speed ($\text{m}\cdot\text{s}^{-1}$) in the swimming direction during the push phase, and in the lateral direction during the underwater phases in back crawl than in front crawl. Swimmers also had larger absolute hand acceleration ($\text{m}\cdot\text{s}^{-2}$) during the pull and push phases in back crawl than in front crawl in all trials. Also, swimmers had lower foot position in the water relative to the water surface in back crawl than in front crawl even though there were no differences in the mean knee position, which probably caused larger cross sectional area facing toward the swimming direction during the stroke cycle in back crawl than in front crawl. These results indirectly suggest the possibility of larger resistive force in back crawl than in front crawl (for further explanation for the relationship between these kinematics and resistive force, see Discussion Section 5.2.3).

In summary, swimmers had smaller Froude efficiency in back crawl than in front crawl because the mean under-water 3D hand speed relative to the centre of mass in back crawl was faster than that in front crawl (which means swimmers produce less useful work for thrust relative to the total work for moving the water in back crawl). The difference in the mean 3D hand speed was caused by swimmer's 3D hand speeds during the pull phase (swimmers had faster 3D hand speed in back crawl), and duration of the release phase (back crawl had longer duration of the release phase) since the mean 3D hand speed is determined by the 3D hand speed in each phase and the duration of the phase relative to the stroke cycle duration. It is also possible that swimmers had larger resistive force in back crawl than in

front crawl, probably because of lower position of the foot in the water, which might have created larger frontal cross sectional area in back crawl.

5.2.3. Summary of Study 2

The purpose of the second study was to investigate biomechanical differences between front crawl and back crawl at the same anaerobic exercise speeds to assess whether front crawl is more efficient than back crawl. To achieve the purpose, kinematic differences between front crawl and back crawl at the same swimming speeds above the anaerobic threshold were investigated.

At the same swimming speed, front crawl was more efficient than back crawl, suggested by higher Froude efficiency, longer stroke length and higher stroke index in front crawl than in back crawl. The difference in stroke length was due to the longer duration of the propulsive phases and possibly larger resistive force. Higher Froude efficiency in front crawl than in back crawl was caused by the longer duration of the release and above-water phases, and faster 3D hand speed relative to the centre of mass during the pull phase in back crawl than in front crawl. The resistive force in back crawl might have been greater than in front crawl because of the lower foot position in the water, which possibly made the frontal cross sectional area larger in back crawl. The possibility of the larger resistive force might be another explanation of higher Froude efficiency in front crawl than in back crawl.

5.3.2. Discussion – Study 3: Kinematic Differences between Front Crawl and Back Crawl at the Same Selected Exercise Intensities.

5.3.2.1. Why were Swimmers Able to Achieve Faster Speed in Front Crawl than in Back Crawl at the Same Selected Exercise Intensities?

At the same exercise intensities, swimmers had faster swimming speeds ($\text{m}\cdot\text{s}^{-1}$) in front crawl than in back crawl (trial-1: 1.43 vs 1.25, trial-2: 1.52 vs 1.34, trial-3: 1.60 vs 1.41, trial-4: 1.70 vs 1.54). Since there were no differences in stroke length ($\text{m}\cdot\text{cycle}^{-1}$) between the two strokes (trial-1: 2.48 vs 2.54, trial-2: 2.44 vs 2.35, trial-3: 2.28 vs 2.25, trial-4: 2.07 vs 2.00), the difference of the swimming speeds were due to the differences in stroke frequency because swimming speed is expressed by multiplication of stroke frequency by stroke length (Counsilman, 1968; Hay, 1993; E. Maglischo, 2003). In this study, swimmers had higher stroke frequency ($\text{cycles}\cdot\text{min}^{-1}$) in front crawl than in back crawl (trial-1: 34.11 vs 30.44, trial-2: 39.40 vs 33.24, trial-3: 43.74 vs 37.53, trial-4: 51.67 vs 44.81).

The higher stroke frequency and similar stroke length in front crawl than in back crawl is in accordance with previous studies. Seifert et al. (2004) calculated stroke frequency and stroke length in front crawl at 50m race speed using 2D video analysis, and Chollet et al. (2008) calculated those in back crawl using the same method. In these studies, Seifert et al. (2004) and Chollet et al. (2008) showed similar stroke length between front crawl and back crawl (front crawl: $2.23 \pm 0.16 \text{ m}\cdot\text{cycle}^{-1}$, back crawl: $2.21 \pm 0.21 \text{ m}\cdot\text{cycle}^{-1}$), and higher stroke frequency in front crawl than in back crawl (front crawl: $49.9 \pm 3.7 \text{ 2 cycles}\cdot\text{min}^{-1}$, back crawl: $44.3 \pm 5.1 \text{ 2 cycles}\cdot\text{min}^{-1}$). Stroke frequency and stroke length were calculated based on the time swimmers achieved from 10m to 22.5m points of the pool in the studies by Seifert et al. (2004) and Chollet et al. (2008), and the methods were different in this study. Nevertheless, considering that both studies and this study quantified the stroke frequency and

length during only the swimming phase (without including the start and turn phases), these two previous studies supported the results of this study.

Thus, at the same exercise intensity, front crawl is faster than back crawl because swimmers can achieve higher stroke frequency in front crawl than in back crawl. In the next section, factors which caused the difference in stroke frequency between the strokes are considered and discussed.

5.3.2.2. Why Is Stroke Frequency Higher in Front Crawl than in Back Crawl?

According to Hay (1993), stroke frequency is determined by the moment of inertia of the arm about the shoulder, the range of motion through which the arm moves during the stroke cycle, and the torque applied to the arm through the shoulder. Thus, in this study, the range of motion of the hand was assessed by kinematics of the arm in both front crawl and back crawl to investigate the cause of the difference in stroke frequency. Although the torque applied to the arm during swimming could not be measured in this study, the possibility of the difference in the torque between front crawl and back crawl were assessed using correlation analysis between isokinetic torque on the land and swimming kinematics. The moment of inertia of the arm was not quantified in this study based on the assumption that the effect of the moment of inertia on the stroke frequency is rather small compared with the effect of the fluid force acting on the hand.

In the next sub-sections, the range of motion of the hand between front crawl and back crawl, and the relationships between the isokinetic torque and front crawl and back crawl performances are discussed.

5.3.2.2.1. Difference in the Arm Range of Motion

In this section, the difference in the arm range of motion during the stroke cycle between the strokes is discussed.

Swimmers had longer 3D hand path distance relative to the centre of mass (m) in back crawl than in front crawl in both under the water (trial-1: 2.47 vs 2.29, trial-2: 2.43 vs 2.32, trial-3: 2.38 vs 2.26, trial-4: 2.37 vs 2.20) and above the water (trial-1: 1.95 vs 1.51, trial-2: 2.00 vs 1.55, trial-3: 2.00 vs 1.53, trial-4: 1.98 vs 1.52). The longer hand path distance under the water in back crawl was due to the longer hand path distance during the release phase (trial-1: 0.61 vs 0.29, trial-2: 0.61 vs 0.28, trial-3: 0.57 vs 0.28, trial-4: 0.63 vs 0.25), because of the additional upsweep and down-sweep movement in this phase in back crawl (see Discussion Section 5.3.1.2.2.). These results suggest that the range of motion of the hand in back crawl was larger than that in front crawl both in the above-water phase and the release phases, which makes the duration of the release phase (trial-1: 0.11 vs 0.44, trial-2: 0.09 vs 0.41, trial-3: 0.09 vs 0.33, trial-4: 0.07 vs 0.26) and the above-water phase longer in back crawl (trial-1: 0.47 vs 0.71, trial-2: 0.42 vs 0.64, trial-3: 0.39 vs 0.57, trial-4: 0.34 vs 0.45) than in front crawl (and thus caused lower stroke frequency in back crawl).

Thus, it can be concluded that the higher stroke frequency in front crawl than in back crawl was due to the smaller range of motion during the release and the above-water phases which made the duration of these phases shorter.

Another possible explanation - the possibility of the difference in the torque applied on the arm between front crawl and back crawl are discussed in section 5.3.2.2.3.

5.3.2.2.2. The Effect of Coordination between Left and Right Arm Strokes on the Stroke Frequency

Hay (1993) did not refer to the effect of coordination between the left and right arms on stroke frequency. However, it is possibly one of the primary factors which affects the difference in stroke frequency between front crawl and back crawl. The earlier in the underwater phase the swimmer makes the entry of the other arm, the shorter the above-water phase duration, and thus, shorter stroke cycle duration as long as the speed of arm rotation above the water does not exceed its maximum achievable speed (Figure 5.12). This is based on the assumption that the swimmer adjusts the speed of the arm rotation in the above the water phase to that in the underwater phase, rather than vice-versa. This assumption is logical since the swimmer cannot move their arm in the water faster than in above-water phase because of water resistance.

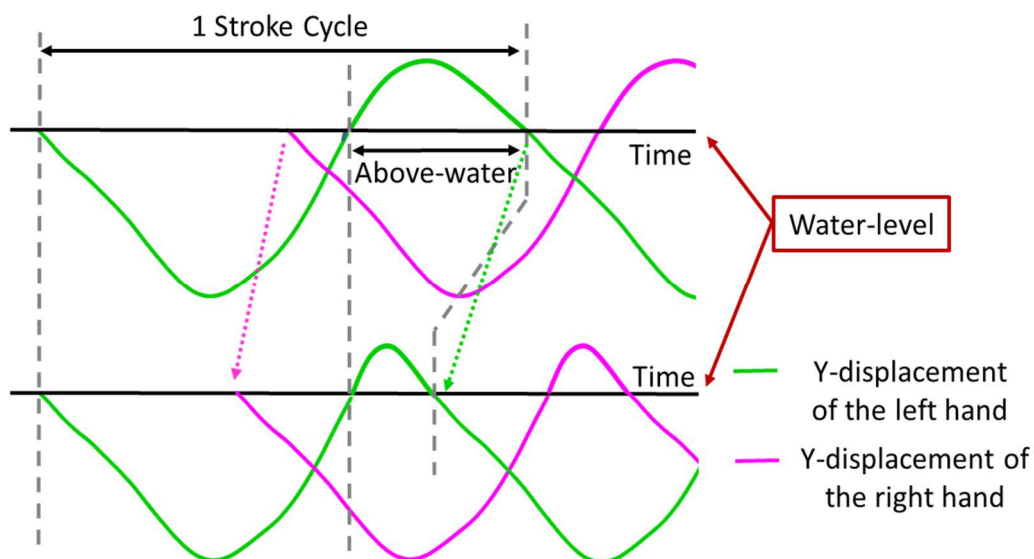


Figure 5. 12: A model of the effect of the coordination between the left and right hands (timing of the hand entry) on the duration of a stroke cycle.

E. Maglischo (2003) suggested that a front crawl swimmer's arm enters the water while other arm is in the middle of the stroke (when the hand is completing the in-sweep phase) in front crawl, whereas the arm enters the water when the other arm is in nearly the end of the stroke (when the hand is completing the second down-sweep phase) in back crawl. In this study, swimmers entered their hand in the water at the point of 68.7-70.1% of the underwater phase of the other arm in front crawl, and at the point of 76.4-78.1 % of the underwater phase of the other hand in back crawl. The differences of the timing were significant in trial-1, 2, and 3 (trial-1: 70.2 % vs 78.1 %, $p < 0.01$, $d = 1.92$. trial-2: 68.8% vs 77.7%, $p = 0.01$, $d = 1.68$. trial-3: 69.7% vs 77.9%, $p < 0.05$, $d = 1.09$), and although the difference was not significant in trial-1, the effect size was large (69.9% vs 76.4%, $p = 0.09$, $d = 0.96$). The timing of the entry of the hand corresponded to the push or the beginning of the pull phase in front crawl, and the release phase in back crawl in every trial. These results are in agreement with the statement by E. Maglischo (2003).

Figure 5.13 shows an example of the effect of the timing of the hand entry on the difference in the stroke cycle duration between front crawl and back crawl (based on the results from trial-4 in front crawl and back crawl of the same swimmer). In the figure, the time lines are normalised by the duration of the underwater phase of the right hand. This swimmer entered the hand at 76.6% of the underwater phase of the other hand in back crawl, and at 71.8% of the underwater phase of the other hand in front crawl, thus the difference is 5.8% for one hand entry. Thus, if the duration of the underwater phase was the same between the strokes, and assuming the hand entry timing is the same in both left and right hand, the difference in the entry timing would make the stroke cycle duration for 11.6 % of the underwater phase duration (seconds) shorter in front crawl than in back crawl.

Obviously, the duration of the underwater phase in front crawl and back crawl are not exactly the same, and thus the exact duration (seconds) in the stroke cycle which is affected by the difference in the timing of the hand entry could not be calculated. Nevertheless,

considering the potential effect of the hand entry timing on the stroke cycle duration (see Figure 5.12), and the results from the present study, it is logical to conclude that the difference in the hand entry timing between front crawl and back crawl affected the difference in the stroke cycle duration (and thus, stroke frequency).

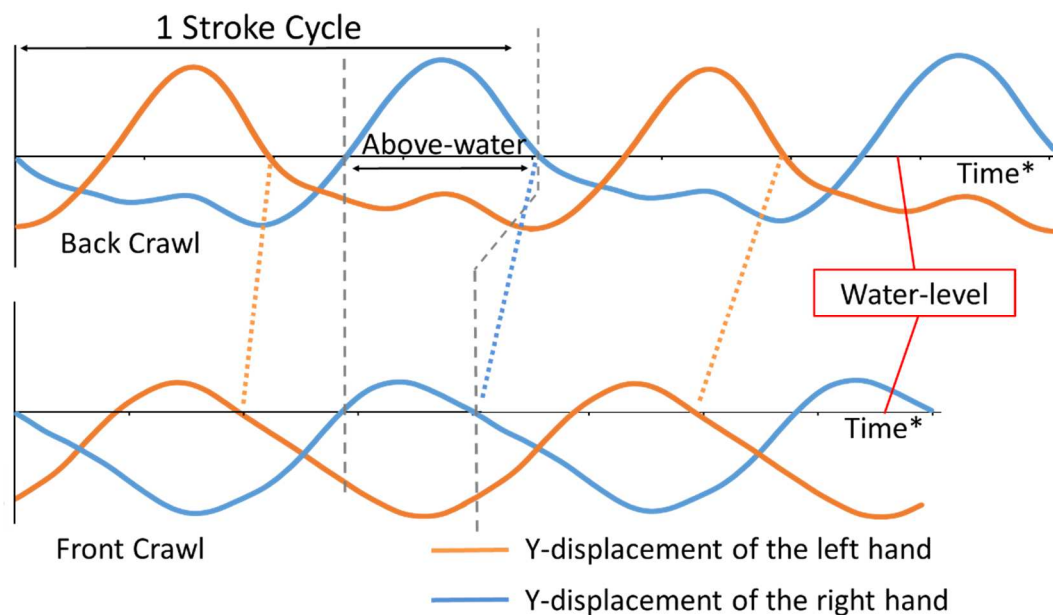


Figure 5. 13: The effect of the coordination between the left and right hands (timing of the hand entry) on the difference in the duration of a stroke cycle between front crawl and back crawl. *The time is normalised by the duration of the underwater phase of the right hand

5.3.2.2.3. Are There Differences in Torque Applied to the Upper Limbs between Front Crawl and Back Crawl?

In this study, the torque applied to the upper limbs by the water could not be assessed.

However, correlations between shoulder isokinetic torque on the land and kinematics during front crawl and back crawl at maximum speed trials (such as mean velocity, stroke frequency, and hand speed) were determined to assess the possible differences in the torque during swimming between front crawl and back crawl.

One of the main purposes of the correlation analysis between isokinetic torques and kinematics was to assess the relationships between shoulder extension torque and swimming performance and shoulder adduction torque and the swimming performance at maximum effort (such as swimming speed, stroke frequency, stroke length). This measurement was based on the prospect that the primary shoulder motion is shoulder extension in front crawl (Miyashita and Kanehisa, 1979) and shoulder adduction in back crawl (Pink et al., 1992). Thus, it may be that front crawl would be capable of achieving higher stroke frequencies than back crawl since shoulder extension can produce larger isokinetic torque, and therefore, allow faster movement of the hands through the water, than shoulder adduction (Cahalan et al., 1991).

The relationship between shoulder internal rotation torque and swimming performance was also of interest and another purpose of the correlation analysis. This was based on the prospect that internal rotation may contribute more to hand motion in one stroke than the other. One possible source of differences is that swimmers internally rotate their shoulder from the middle and the end of the stroke in front crawl, but only in the end of the stroke in back crawl (Richardson et al., 1979).

In this study, there was a significant correlation between normalised shoulder extension peak torque (extension peak torque normalised by the body weight) and normalised stroke length

(stroke length normalised by the height) in front crawl ($r=-0.63$, $p<0.05$). Although there was no correlation between the swimming speed and shoulder extension torque values, considering that stroke length is a primary factor which determines the swimming speed, the finding in this study was indirectly in line with Miyashita and Kanehisa (1979) who reported a negative correlation between shoulder extension peak torque and 100-m front crawl best record. However, there was a stronger correlation between the shoulder adduction peak torque and normalised stroke length ($r=-0.79$, $p<0.01$). There were also strong significant positive correlations between normalised shoulder adduction peak torques and stroke frequency in both front crawl and back crawl, which means in both front crawl and back crawl, the factor which affects swimmers' stroke frequency is shoulder adduction. Although shoulder extension torque probably contribute to the normalised stroke length in front crawl, the contribution of shoulder adduction torque is probably stronger considering the stronger correlation between normalised stroke length and shoulder adduction torque than that between normalised stroke length and shoulder extension torque. During the maximum swimming trials, swimmers had over 150 degrees of the mean shoulder horizontal abduction during the pull phase, which was due mainly to the shoulder adduction rather than shoulder extension. Therefore it is logical that there were strong correlations between the shoulder adduction peak torque and stroke parameters.

The study by Miyashita and Kanehisa (1979) has been the only research in which the relationship between shoulder isokinetic torque and swimming performance is reported. However, Miyashita and Kanehisa only reported the correlation between peak shoulder extension torque and 100m front crawl record, and no other correlation data using other isokinetic torque variables were reported. Furthermore, even though they reported a negative correlation between shoulder isokinetic extension torque and 100m front crawl record, there were no significant correlations between swimming speed and shoulder isokinetic extension torque values. This might have been associated with the variability in age of the participants

(11 to 21 years) in the study by Miyashita and Kanehisa (1979). Since both muscular strength and swimming performance are increased significantly during puberty (Jürimäe et al., 2007; Seger and Thorstensson, 2000), the results of their study might have been biased by variability in the anthropometric characteristics in the participants.

Although there is no shoulder flexion movement in front crawl, there were correlations between flexion peak torque and front crawl stroke frequency/length and normalised stroke length. These correlations may reflect the association of strength between adduction peak torque and flexion peak torque ($r=0.7$, $p<0.03$) rather than being a contributing factor to performance in front crawl.

There were significant negative correlations between shoulder adduction torque and the underwater phase duration in both front crawl and back crawl (front crawl: $r=-0.82$, $p<0.01$, back crawl: $r=-0.88$, $p<0.01$). These results are reasonable considering the strong correlation between stroke frequency and adduction torque.

There were also significant correlations between internal rotation peak torque in both 60 and 180 $\text{deg}\cdot\text{s}^{-1}$ trials and the underwater phase duration in front crawl (60 $\text{deg}\cdot\text{s}^{-1}$: $r=-0.76$, $p<0.05$, 180 $\text{deg}\cdot\text{s}^{-1}$: $r=-0.79$, $p<0.01$), but not in back crawl. Thus, it is possible that internal rotation has a role to shorten the duration of underwater phase (and thus, to increase stroke frequency) in front crawl.

There have been studies which investigated the importance of shoulder internal rotation during front crawl. Ceccon et al. (2012) assessed the internal rotation during front crawl with 31 markers on the trunk and the arm, and showed large internal rotation value during the push phase. Also, Olivier et al. (2008) evaluated the difference in the strength of shoulder internal/external isokinetic torque and the balance of the internal/external isokinetic torque between front crawl swimmers and non-swimmers. Olivier et al. (2008) concluded that front crawl swimmers had stronger isokinetic torque in internal shoulder rotation in relation to

external shoulder rotation torque than non-swimmers. The results of these studies supported the significant correlation between front crawl underwater phase duration and the internal rotation torque in this study. However, there have been no studies which investigated shoulder internal rotation during back crawl.

The internal rotation during the stroke could not be assessed from the digitised data in this study, since in most of both the pull and push phases, swimmers' elbow angle exceeded 135 degrees. Gordon & Dapena (2006) reported that shoulder internal and external rotation cannot be measured accurately over the elbow joint angle of 135 degrees if the rotation is measured using only one skin marker on each joint, which was the case in this study.

This study found a significant correlation between shoulder internal rotation isokinetic torque and underwater phase duration only in front crawl and not in back crawl, and thus it perhaps affected the difference in stroke frequency between the strokes. However, the effect of the difference on the stroke frequency between the strokes could not be concluded in this study since further study is necessary to investigate swimmer's shoulder internal rotation during swimming, especially in back crawl.

5.2.3. Summary of Study 3

The purpose of the third study was to investigate biomechanical differences between front crawl and back crawl at the same anaerobic exercise intensities to assess which kinematic factors make front crawl to be faster than back crawl. To achieve the purpose, kinematic differences between front crawl and back crawl at the same exercise intensity above the anaerobic threshold, and the difference in the relationship between isokinetic torque and swimming performance between front crawl and back crawl were investigated.

At the same exercise intensity, front crawl was faster than back crawl because swimmers could achieve higher stroke frequency in front crawl than in back crawl. Swimmers could achieve higher stroke frequency in front crawl because of the following reasons. Firstly, the range of motion of the hand (3D hand path distance relative to the centre of mass) was smaller during the stroke in front crawl, especially during the release phase, than in back crawl, and thus swimmers could complete the stroke in shorter duration in front crawl than in back crawl. Secondly, the timing of the hand entry in relation to the underwater phase of the other hand was earlier in front crawl than in back crawl, which made the duration of the above-water phase in front crawl shorter than that in back crawl.

Contrary to expectation based on previous studies, there were strong correlations between shoulder adduction torque and swimming performance in both front crawl and back crawl. Even though there was a significant correlation between normalised shoulder extension peak torque and normalised stroke length, the correlation was weaker than correlations between normalised adduction peak torque and kinematic variables. Swimmers had strong correlation between underwater phase duration and internal rotation torque in front crawl, but not in back crawl. It is possible that the internal rotation contributes to the higher stroke frequency in front crawl than back crawl, but there was insufficient evidence from this study and previous studies to support the possibility. Thus, further investigation is necessary to assess the potential advantage of internal rotation to high stroke frequency.

Chapter Six
Conclusion

The purposes of this study were:

1. To quantify both physiological and biomechanical differences at an aerobic exercise intensity to assess whether front crawl is more economical than back crawl at this intensity (Study 1).
2. To investigate biomechanical differences between front crawl and back crawl at the same anaerobic speeds to assess whether front crawl is more efficient than back crawl at this intensity (Study 2).
3. To explore the differences between front crawl and back crawl at the same anaerobic intensities to assess which kinematic factors make front crawl to be faster than back crawl, and to investigate the relationship between shoulder isokinetic torque and kinematic variables in front crawl and back crawl (Study 3).

To achieve the purposes, physiological and biomechanical variables were measured based on the model below.

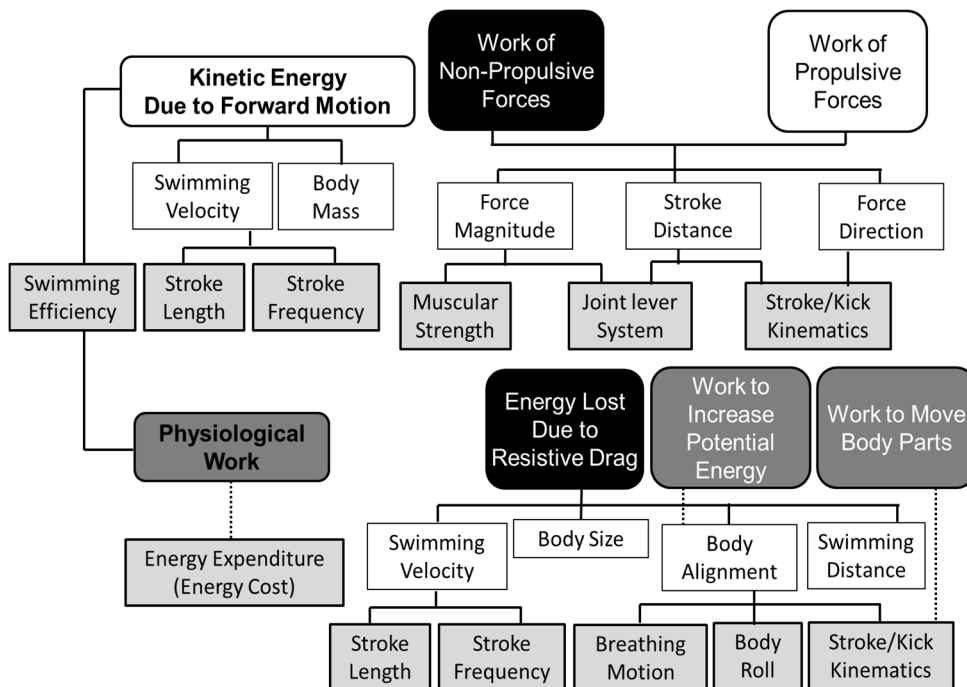


Figure 6. 1 (Figure 1.2): Factors which contribute to swimming performance based on Figure 1.1.

6.1. The Differences between Front Crawl and Back Crawl below the Anaerobic Threshold

Front crawl is more economical and efficient than back crawl at an aerobic exercise intensity because swimmers waste less energy during the non-propulsive phases (entry, release, and above-water phases) and it makes mechanical efficiency higher in front crawl than in back crawl. Swimmers might experience larger resistive forces during back crawl than in front crawl, however, further investigation is necessary to explore the difference in forces between front crawl and back crawl.

6.2. The Differences between Front Crawl and Back Crawl above the Anaerobic Threshold

6.2.1. The Differences between Front Crawl and Back Crawl above the Anaerobic Threshold at the Same Selected Speed

Front crawl is more efficient than back crawl at the same swimming speeds above the anaerobic threshold.

The first factor which suggests higher efficiency in front crawl than in back crawl is larger stroke index, which is due to longer stroke length. The longer stroke length in front crawl than in back crawl is due to the longer duration of the propulsive phases and probably smaller resistive impulse during the stroke cycle in front crawl than in back crawl.

The second factor which determines higher efficiency (Froude efficiency) in front crawl than in back crawl is slower 3D hand speed relative to the centre of mass in front crawl than in back crawl. The faster 3D hand speed during the stroke cycle in back crawl than in front crawl is due to the faster 3D hand speed during the pull phase, and longer relative duration

(the duration of the phase in relation to the whole stroke cycle duration) of the release and above-water phases in back crawl than in front crawl.

6.2.2. The Differences between Front Crawl and Back Crawl above the Anaerobic Threshold at the Same Selected Exercise Intensity

Front crawl is faster than back crawl at the same selected exercise intensities at anaerobic exercise intensities, and this is due to the higher stroke frequency in front crawl. The higher stroke frequency in front crawl than in back crawl is due mainly to two kinematic differences in the upper limbs between the strokes.

The first difference is the longer hand path distance during the release phases in back crawl than in front crawl, which makes the duration of the release phase longer in back crawl.

The second kinematic difference which affects the difference in the stroke frequency is the earlier timing of the hand entry in relation to the underwater phase of the other hand in front crawl than in back crawl, because the earlier hand entry potentially shorten the duration of the above-water phase.

6.2.3. The Relationships between Swimming Performance and Shoulder Isokinetic Torques in Front Crawl and Back Crawl.

Shoulder adduction is an important factor in both front crawl than in back crawl. Even though shoulder extension torque probably contributes to normalised stroke length, which indirectly supported the correlation between shoulder extension isokinetic torque and front crawl performance (100m front crawl best record) of swimmers in a previous study

(Miyashita & Kanehisa, 1979), shoulder adduction torque probably has larger contribution on the kinematic variables in front crawl.

In this study, the possibility that shoulder internal rotation is more important to determine the stroke frequency in front crawl than it is in back crawl was suggested from correlation analysis. However, there was little kinematic information which supported this possibility because of methodological limitation. Further investigation will be necessary to establish the difference in the importance of the shoulder internal rotation between front crawl than in back crawl.

6.3. Practical Implications

For swimmers who have large yaw angle fluctuation in back crawl, it would be helpful to minimise the lateral distance between the hand and the centre of mass which would reduce their yaw angle fluctuation, and thus, resistive forces in back crawl. It is potentially also important to reduce the vertical range of motion of the foot would probably reduce the frontal cross sectional area.

It is important for swimmers to improve their swimming efficiency, consequently, to have low energy cost, because to have less energy cost benefit swimmers to maintain fast swimming speed for longer duration (i.e. with a given expended energy and a given distance to travel, swimmers with lower energy cost achieve the targeted distance in shorter time; Capelli, 1999). To improve the mechanical efficiency in back crawl, it is necessary to minimise the motions which do not contribute to the propulsion. The potential phase in which swimmers could reduce their motion would probably be the release phase, in which the second down-sweep and the second up-sweep motions are conducted. To reduce the

duration of the release phase by means of minimising the second down-sweep motion would also help the swimmer to obtain higher stroke frequency.

Swimmers should focus on shoulder adduction strength, rather than shoulder extension strength when they conduct dry-land training to improve their stroke frequency in front crawl and back crawl.

6.4. Limitations and Recommendations

In this study, the resistive forces were not actually measured, and thus, the difference in the resistive force between front crawl and back crawl is still unknown. Currently, Measuring Active Drag system (MAD-system: Hollander et al., 1986) is the widely used method to assess the resistive force during swimming. However, this method is only applicable for arm-only front crawl swimming, and so the mean resistive force during back crawl cannot be estimated with the MAD-system (Barbosa et al., 2011). Thus, it would be necessary to assess the difference in the resistive force between front crawl and back crawl using another method such as Velocity Perturbation Method (VPM: Kolmogorov & Duplishcheva, 1992) or Assisted Towing Method (ATM: Alcock & Mason, 2007). Since the resistive force is affected by the body size of the swimmer, front crawl and back crawl for the resistive force assessment will have to be conducted by the same swimmer. Nevertheless, the accuracy of the estimation of the resistive force is still controversial, and thus, it will also be necessary to establish an accurate method of assessing resistive force in swimming.

In this study, vertical displacements of knee and ankle were investigated as indicator of cross sectional area produced by the kicking motion. However, the cross sectional area itself was not investigated in this study and it is not clear if the position of these joints actually reflects

the cross sectional area. Further investigation will be necessary to verify the relationship between vertical displacements of knee and ankle and cross sectional area produced by the lower limbs.

The difference in the propulsive force between front crawl and back crawl should also be investigated in the future. In this study, it was assumed that the faster hand speed and larger hand acceleration and deceleration would generate larger propulsive forces based on the mathematical model by Sanders (1999) and experimental results by Kudo et al. (2012; 2013). However, Kudo et al. (2012; 2013) only measured the relationships between the propulsive force and the hand speed, acceleration and deceleration only in front crawl, and it is not clear if the results are applicable in back crawl. Thus, it will be necessary to establish the relationships between the hand kinematics and the propulsive force generated by the hand by experimental studies (e.g. by means of the pressure sensors).

Another limitation was that the difference in the energy expenditure between front crawl and back crawl above the anaerobic threshold could not be assessed in this study, and the difference should be investigated in the future. Currently the most common method for measuring the anaerobic energy expenditure in swimming was to use the blood lactate accumulation value (Barbosa et al., 2008; Fernandes, Billat, et al., 2006; Figueiredo, Barbosa, et al., 2012; Figueiredo, Zamparo, et al., 2011; Zamparo, Bonifazi, et al., 2005; Zamparo et al., 2000). The problem in this method are that blood lactates severely underestimate muscle lactate concentrations (Scott & Kemp, 2005), and the individual differences in the energy equivalent of the lactate accumulation are too large to ignore (Thevelein et al., 1984). Thus, in future studies, it will be necessary to assess the individual energy equivalent before applying the blood lactate accumulation values to the energy expenditure calculation (e.g. by comparing the blood lactate and muscle lactate accumulation using biopsy: Karlsson, Nordesjo, Jorfeldt, & Saltin, 1972; Karlsson & Saltin, 1970).

Although the accuracy and reliability of measuring energy expenditure using the combination of k4b² and AquaTrainer[®] snorkel have been previously investigated on the land, it is unsure if the use of the apparatus produces accurate results in the water, which is due to the difficulty of measuring energy expenditure using different respiratory masks. To not know the accuracy and reliability of the energy expenditure measurement in the water is a technical limitation of this study.

The internal rotation during the stroke cycle in front crawl and back crawl could not be investigated in this study because the elbow joint angle of over 135 degrees (which does not produce accurate internal and external rotation angles in the motion analysis with single joint markers) during the pull and push phases (Gordon & Dapena, 2006). To investigate the difference in the importance of shoulder internal rotation between the strokes, it will be necessary to conduct detailed 3D motion analysis with additional joint markers so that shoulder internal and external angles can be calculated when swimmers have the elbow joint angle of over 135 degrees.

In this study, some variables had large digitise-redigitise reliability errors, especially in the intra-cycle velocity variation and net impulse. Even though these variables were considered as indicators of resistive force the swimmer experienced during the analysed stroke cycle, it should be recognised the arguments based on these results might have been biased because of the errors.

The accuracy of the pace control device was another potential limitation of this study. In Study 1, even though swimmers achieved identical final time in 300m front crawl and back crawl, the COM speeds during one stroke cycle in front crawl and back crawl were not very identical (even though there was no significant difference and the effect size was small-medium). These results suggested the possibility that the COM speeds of the participants varied among the stroke cycles during the 300m trials (even though the speeds were close to

the instructed speeds), which might have affected the kinematic variables analysed in this study.

In this study, total of 244 significant results (164 significant differences, 51 significant main effects, and 9 significant correlations) were obtained at significance level of 1%, and total of 60 significant results (43 significant differences, 4 significant main effects, and 13 significant correlations) were found at significance level of 5%. These data suggest that 2 or 3 significant results out of the results at each significant level were possibly due to the type I error.

In this study, the calculation of Froude efficiency was based on the assumption of constant COM and 3D hand speed, which is not the case in actual swimming. It means that the results of Froude efficiency in this study did not reflect the differences in hand acceleration and deceleration between front crawl and back crawl.

The wrist and ankle were used for calculation of hand and foot kinematics in this study. This calculation had an advantage of minimising the error due to the difficulty of identifying the toe and fingertip because of the turbulence and bubbles around the hand and foot. However, this approach also had a limitation that the effects of dorsi-flexion and plantar-flexion of the ankle and wrist on the hand and foot kinematics were not reflected in the results of this study.

Another limitation in this study was that the blood sampling timing in the incremental protocol was immediately after each swimming stage, which was not the timing where swimmers show the highest blood lactate value. It suggests the possibility of the blood lactate values used to determine the testing speeds in this study being underestimated. Nevertheless, considering the accuracy of assessing the anaerobic threshold using the protocol (Fernandes et al., 2011), and that the swimmers successfully achieved the same

swimming speed in Study 2 of this study, the effect of the early blood sampling timing on the results of this study was probably small.

In Study 1, a respiratory snorkel was used to collect swimmer's expired gas. Although it was reported that to wear the snorkel does not change stroke frequency and stroke length of the swimmer in front crawl and that the snorkel does not increase the hydrodynamic drag in front crawl, it is unclear if this is the case in back crawl. It is also unclear if other kinematic variables are affected by the snorkel or not. Considering that to wear a snorkel put additional mass on the head of the swimmer, it is possible that it affects the body alignment and/or the body position of the swimmer which might alter some kinematics during swimming. This possible effect of wearing a snorkel on kinematic parameters is another possible limitation in this study. The effect of wearing snorkel on detailed kinematic variables in front crawl and back crawl is a topic to be explored in the future.

In this study, correlation between kinematic variables and isokinetic torque was assessed using isokinetic torque values measured in angular velocity of 60 degrees·s⁻¹ and 180 degrees·s⁻¹, which are slower than upper limbs speed in swimming (which corresponds to more than 300 degrees·s⁻¹). This was due to the inaccuracy of measuring isokinetic torque at angular speeds faster than 180 degrees·s⁻¹, and it was a technical limitation that the correlation between kinematic variables in swimming and isokinetic torque measured in angular velocity similar to upper limb speed in swimming could not be assessed.

6.5. Overall Conclusion

Despite all the limitations, this study was the first investigation which described both physiological and biomechanical differences between different swimming strokes. This study investigated many physiological and biomechanical differences between front crawl and back crawl, and suggested why and how much front crawl is faster, more economical and efficient than back crawl. It is expected that this study will contribute to swimming research by leading the future comprehensive investigations of the differences between each swimming stroke.

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Appendix

Table AP. 1: Five times digitise-redigitise reliability in back crawl.

Variables (Back crawl)	Mean	Standard Deviation	Coefficient of Variation	95% Confidence Intervals	
				Lower	Upper
Stroke length (m·cycle ⁻¹)	2.25	0.01	0.32	2.24	2.26
Cycle Time (s)	1.47	0.00	0.29	1.46	1.47
Stroke frequency (cycles·min ⁻¹)	40.90	0.12	0.30	40.75	41.05
Stroke index (m ² ·cycle ⁻¹ ·s ⁻¹)	3.45	0.02	0.55	3.43	3.48
Velocity of the centre of mass (m·s ⁻¹)	1.53	0.00	0.32	1.53	1.54
Intra-cycle maximum velocity (m·s ⁻¹)	1.78	0.01	0.50	1.77	1.79
Intra-cycle minimum velocity (m·s ⁻¹)	1.17	0.06	4.70	1.10	1.24
Intra-cycle velocity variation (m·s ⁻¹)	0.61	0.05	8.43	0.55	0.67
Entry phase duration (s)	0.21	0.01	4.52	0.19	0.22
Pull phase duration (s)	0.21	0.01	2.66	0.20	0.22
Push phase duration (s)	0.18	0.00	2.39	0.17	0.18
Release phase duration (s)	0.34	0.00	1.23	0.34	0.35
Above-water phase duration (s)	0.53	0.00	0.77	0.52	0.53
Propulsive phase duration (s)	0.39	0.01	1.43	0.38	0.40
Non-propulsive phase duration (s)	1.08	0.01	0.76	1.07	1.09
Shoulder roll angle (degrees)	53.98	1.15	2.14	52.55	55.41
Hip roll angle (degrees)	42.73	1.92	4.50	40.34	45.12
Hand speed during the pull phase (m·s ⁻¹)	-1.09	0.05	4.91	-1.16	-1.03
Hand speed during the push phase (m·s ⁻¹)	-1.95	0.05	2.68	-2.02	-1.89
Mean hand speed during the underwater phases in the vertical direction (m·s ⁻²)	1.04	0.01	0.59	1.04	1.05
Mean hand speed during the underwater phases in the lateral direction (m·s ⁻²)	0.97	0.01	1.38	0.96	0.99
Hand acceleration during the pull phase (m·s ⁻²)	-11.44	0.15	1.27	-11.62	-11.25
Hand acceleration during the push phase (m·s ⁻²)	10.48	0.31	2.95	10.09	10.86
Total 3D hand path distance (m)	4.31	0.01	0.20	4.30	4.32
Entry phase 3D hand path distance (m)	0.34	0.01	3.77	0.32	0.35
Pull phase 3D hand path distance (m)	0.68	0.01	2.00	0.66	0.69
Push phase 3D hand path distance (m)	0.70	0.01	1.61	0.69	0.72
Release phase 3D hand path distance (m)	0.70	0.01	2.03	0.68	0.71
Above-water phase 3D hand path distance (m)	2.09	0.01	0.67	2.07	2.10
Total 3D foot path distance (m)	2.31	0.02	0.84	2.28	2.33
3D hand speed (m·s ⁻¹)	2.94	0.00	0.13	2.94	2.94
3D foot speed (m·s ⁻¹)	1.57	0.01	0.78	1.56	1.59
Range of motion of the foot in the vertical direction (m)	0.46	0.01	2.87	0.45	0.48
Range of motion of the foot in the lateral direction (m)	0.37	0.01	3.50	0.35	0.38
Mean shoulder horizontal abduction angle during the pull phase (degrees)	165.46	0.69	0.42	164.60	166.32
Mean shoulder horizontal abduction angle during the push phase (degrees)	163.18	2.71	1.66	159.81	166.54
Mean elbow angle during the pull phase (degrees)	127.33	1.03	0.81	126.05	128.61
Mean elbow angle during the push phase (degrees)	112.79	2.25	1.99	110.00	115.58
Net impulse (Ns) during the propulsive phase	12.28	1.15	9.36	10.85	13.70
Maximum lateral distance between the hand and COM (m)	0.50	0.01	1.00	0.50	0.51
COM maximum vertical displacement (m)	-0.15	0.00	0.86	-0.15	-0.15
COM minimum vertical displacement (m)	-0.20	0.00	0.53	-0.20	-0.20
COM mean vertical displacement (m)	-0.17	0.00	0.39	-0.17	-0.17
Shoulder mean vertical displacement (m)	-0.09	0.00	2.57	-0.09	-0.09
Hip mean vertical displacement (m)	-0.23	0.00	0.23	-0.23	-0.23
Knee minimum vertical displacement (m)	-0.38	0.00	0.64	-0.38	-0.37
Knee mean vertical displacement (m)	-0.23	0.00	0.54	-0.24	-0.23
Foot minimum vertical displacement (m)	-0.51	0.01	1.73	-0.52	-0.50
Foot mean vertical displacement (m)	-0.33	0.00	0.71	-0.33	-0.33
Contribution of the entry phase on the 3D hand speed	0.23	0.01	3.37	0.22	0.24
Contribution of the pull phase on the 3D hand speed	0.47	0.01	1.33	0.46	0.48
Contribution of the push phase on the 3D hand speed	0.48	0.01	1.71	0.47	0.49
Contribution of the release phase on the 3D hand speed	0.47	0.01	1.42	0.47	0.48
Contribution of the above-water phase on the 3D hand speed	1.42	0.01	0.92	1.41	1.44
Timing index (%)	77.85	0.84	1.08	76.80	78.89
Froude efficiency (%)	0.52	0.00	0.26	0.52	0.52
Yaw angle fluctuation (degrees)	12.59	0.72	5.73	11.70	13.49

Table AP. 2: Five times digitise-redigitise reliability in front crawl.

Variables (Front crawl)	Mean	Standard Deviation	Coefficient of Variation	95% Confidence Intervals	
				Lower	Upper
Stroke length (m·cycle ⁻¹)	2.63	0.01	0.48	2.62	2.65
Cycle Time (s)	1.59	0.01	0.55	1.58	1.60
Stroke frequency (cycles·min ⁻¹)	37.70	0.21	0.55	37.45	37.96
Stroke index (m ² ·cycle ⁻¹ ·s ⁻¹)	4.36	0.04	0.87	4.31	4.40
Velocity of the centre of mass (m·s ⁻¹)	1.66	0.01	0.54	1.64	1.67
Intra-cycle maximum velocity (m·s ⁻¹)	1.89	0.05	2.88	1.83	1.96
Intra-cycle minimum velocity (m·s ⁻¹)	1.42	0.07	4.58	1.34	1.50
Intra-cycle velocity variation (m·s ⁻¹)	0.47	0.05	10.99	0.41	0.54
Entry phase duration (s)	0.52	0.01	1.18	0.51	0.53
Pull phase duration (s)	0.23	0.02	7.59	0.21	0.25
Push phase duration (s)	0.27	0.02	5.92	0.25	0.29
Release phase duration (s)	0.07	0.02	20.00	0.06	0.09
Above-water phase duration (s)	0.49	0.00	0.97	0.49	0.50
Propulsive phase duration (s)	0.50	0.02	3.09	0.48	0.52
Non-propulsive phase duration (s)	1.09	0.02	2.02	1.06	1.12
Shoulder roll angle (degrees)	57.05	1.83	3.20	54.78	59.32
Hip roll angle (degrees)	46.59	1.89	4.06	44.24	48.95
Hand speed during the pull phase (m·s ⁻¹)	-1.15	0.04	3.81	-1.20	-1.09
Hand speed during the push phase (m·s ⁻¹)	-1.26	0.06	4.47	-1.33	-1.19
Mean hand speed during the underwater phases in the vertical direction (m·s ⁻²)	1.08	0.00	0.45	1.07	1.08
Mean hand speed during the underwater phases in the lateral direction (m·s ⁻²)	0.41	0.00	1.19	0.40	0.41
Hand acceleration during the pull phase (m·s ⁻²)	-8.37	0.26	3.15	-8.69	-8.04
Hand acceleration during the push phase (m·s ⁻²)	7.70	0.22	2.87	7.43	7.98
Total 3D hand path distance (m)	3.97	0.05	1.30	3.90	4.03
Entry phase 3D hand path distance (m)	0.52	0.02	4.60	0.49	0.54
Pull phase 3D hand path distance (m)	0.73	0.03	4.35	0.69	0.77
Push phase 3D hand path distance (m)	0.94	0.03	3.33	0.90	0.98
Release phase 3D hand path distance (m)	0.19	0.02	11.06	0.16	0.21
Above-water phase 3D hand path distance (m)	1.80	0.01	0.49	1.78	1.81
Total 3D foot path distance (m)	2.38	0.03	1.39	2.34	2.42
3D hand speed (m·s ⁻¹)	2.49	0.02	0.79	2.47	2.52
3D foot speed (m·s ⁻¹)	1.50	0.02	1.18	1.47	1.52
Range of motion of the foot in the vertical direction (m)	0.53	0.01	1.18	0.52	0.54
Range of motion of the foot in the lateral direction (m)	0.24	0.00	1.21	0.24	0.24
Mean shoulder horizontal abduction angle during the pull phase (degrees)	164.42	5.91	3.59	157.08	171.75
Mean shoulder horizontal abduction angle during the push phase (degrees)	129.49	5.04	3.89	123.23	135.74
Mean elbow angle during the pull phase (degrees)	131.41	2.47	1.88	128.35	134.47
Mean elbow angle during the push phase (degrees)	120.49	2.98	2.47	116.79	124.19
Net impulse (Ns) during the propulsive phase	14.31	1.13	7.91	12.91	15.72
Maximum lateral distance between the hand and COM (m)	0.33	0.01	1.54	0.32	0.33
COM maximum vertical displacement (m)	-0.11	0.00	1.58	-0.11	-0.11
COM minimum vertical displacement (m)	-0.19	0.00	1.02	-0.19	-0.19
COM mean vertical displacement (m)	-0.14	0.00	1.49	-0.15	-0.14
Shoulder mean vertical displacement (m)	-0.05	0.00	2.84	-0.06	-0.05
Hip mean vertical displacement (m)	-0.21	0.00	0.77	-0.21	-0.21
Knee minimum vertical displacement (m)	-0.33	0.00	0.63	-0.33	-0.33
Knee mean vertical displacement (m)	-0.24	0.00	0.69	-0.24	-0.23
Foot minimum vertical displacement (m)	-0.40	0.01	1.61	-0.41	-0.39
Foot mean vertical displacement (m)	-0.20	0.00	0.43	-0.20	-0.20
Contribution of the entry phase on the 3D hand speed	0.32	0.01	4.31	0.31	0.34
Contribution of the pull phase on the 3D hand speed	0.46	0.02	4.93	0.43	0.49
Contribution of the push phase on the 3D hand speed	0.59	0.02	3.01	0.57	0.61
Contribution of the release phase on the 3D hand speed	0.15	0.01	9.78	0.13	0.17
Contribution of the above-water phase on the 3D hand speed	1.13	0.01	0.48	1.12	1.14
Timing index (%)	66.30	0.38	0.58	65.82	66.77
Froude efficiency (%)	0.66	0.01	1.01	0.66	0.67
Yaw angle fluctuation (degrees)	11.29	0.64	5.66	10.49	12.08

Table AP. 3: Accuracy of 25Hz digitising in back crawl (Differences between 25Hz and 50Hz digitising in 5 different back crawl trials).

Variables (Back crawl)	50Hz Mean	25Hz Mean	Mean difference	SD of the difference	difference (%)
Stroke length (m·cycle ⁻¹)	2.09	2.09	0.00	0.01	0.63
Cycle Time (s)	1.38	1.38	-0.01	0.04	0.46
Stroke frequency (cycles·min ⁻¹)	43.49	43.64	0.15	0.49	0.34
Stroke index (m ² ·cycle ⁻¹ ·s ⁻¹)	3.14	3.17	0.03	0.08	0.85
Velocity of the centre of mass (m·s ⁻¹)	1.51	1.51	0.01	0.04	0.60
Intra-cycle maximum velocity (m·s ⁻¹)	1.75	1.77	0.03	0.03	1.09
Intra-cycle minimum velocity (m·s ⁻¹)	1.31	1.32	0.01	0.04	0.81
Intra-cycle velocity variation (m·s ⁻¹)	0.44	0.45	0.01	0.03	2.79
Entry phase duration (s)	0.24	0.24	0.00	0.01	0.81
Pull phase duration (s)	0.21	0.20	-0.01	0.01	3.72
Push phase duration (s)	0.21	0.22	0.01	0.02	4.02
Release phase duration (s)	0.25	0.25	0.00	0.03	0.61
Above-water phase duration (s)	0.47	0.47	0.00	0.04	0.87
Propulsive phase duration (s)	0.42	0.42	0.00	0.03	0.90
Non-propulsive phase duration (s)	0.96	0.96	0.00	0.04	0.27
Shoulder roll angle (degrees)	45.57	47.49	1.92	1.94	4.04
Hip roll angle (degrees)	35.09	36.93	1.83	1.39	4.97
Hand speed during the pull phase (m·s ⁻¹)	-1.31	-1.34	-0.03	0.03	2.54
Hand speed during the push phase (m·s ⁻¹)	-1.39	-1.42	-0.03	0.04	2.01
Mean hand speed during the underwater phases in the vertical direction (m·s ⁻²)	1.02	1.05	0.03	0.03	2.48
Mean hand speed during the underwater phases in the lateral direction (m·s ⁻²)	0.94	0.97	0.02	0.02	2.51
Hand acceleration during the pull phase (m·s ⁻²)	-10.41	-10.78	-0.37	0.28	3.39
Hand acceleration during the push phase (m·s ⁻²)	5.89	6.02	0.12	0.26	2.07
Total 3D hand path distance (m)	4.11	4.12	0.01	0.04	0.17
Entry phase 3D hand path distance (m)	0.41	0.43	0.02	0.03	2.76
Pull phase 3D hand path distance (m)	0.66	0.66	0.00	0.03	0.32
Push phase 3D hand path distance (m)	0.67	0.70	0.02	0.03	3.49
Release phase 3D hand path distance (m)	0.59	0.57	-0.02	0.03	2.92
Above-water phase 3D hand path distance (m)	1.97	1.94	-0.02	0.02	1.16
Total 3D foot path distance (m)	1.97	2.02	0.05	0.02	2.63
3D hand speed (m·s ⁻¹)	2.98	3.01	0.03	0.08	1.03
3D foot speed (m·s ⁻¹)	1.43	1.47	0.04	0.03	2.73
Range of motion of the foot in the vertical direction (m)	0.38	0.39	0.00	0.00	1.27
Range of motion of the foot in the lateral direction (m)	0.29	0.29	0.00	0.02	1.67
Mean shoulder horizontal abduction angle during the pull phase (degrees)	163.19	162.73	-0.46	1.75	0.28
Mean shoulder horizontal abduction angle during the push phase (degrees)	110.52	111.13	0.61	1.73	0.55
Mean elbow angle during the pull phase (degrees)	137.14	135.12	-2.02	2.04	1.49
Mean elbow angle during the push phase (degrees)	128.05	128.14	0.10	1.41	0.08
Net impulse (Ns) during the propulsive phase	6.60	7.04	-0.44	2.76	6.23
Maximum lateral distance between the hand and COM (m)	0.53	0.53	0.00	0.00	0.72
COM maximum vertical displacement (m)	-0.14	-0.14	0.00	0.00	1.16
COM minimum vertical displacement (m)	-0.18	-0.18	0.00	0.00	1.30
COM mean vertical displacement (m)	-0.16	-0.15	0.00	0.00	1.52
Shoulder mean vertical displacement (m)	-0.09	-0.09	0.00	0.00	1.19
Hip mean vertical displacement (m)	-0.21	-0.20	0.00	0.00	2.35
Knee minimum vertical displacement (m)	-0.30	-0.31	0.00	0.00	1.39
Knee mean vertical displacement (m)	-0.19	-0.19	0.00	0.00	0.25
Foot minimum vertical displacement (m)	-0.46	-0.46	0.00	0.00	0.71
Foot mean vertical displacement (m)	-0.29	-0.29	0.00	0.00	0.33
Contribution of the entry phase on the 3D hand speed	0.33	0.31	0.01	0.00	3.93
Contribution of the pull phase on the 3D hand speed	0.47	0.48	0.01	0.04	0.60
Contribution of the push phase on the 3D hand speed	0.49	0.51	0.00	0.01	3.27
Contribution of the release phase on the 3D hand speed	0.43	0.42	0.01	0.01	1.81
Contribution of the above-water phase on the 3D hand speed	1.42	1.42	0.01	0.01	0.65
Timing index (%)	77.03	76.56	-0.47	0.63	0.62
Froude efficiency (%)	0.51	0.50	0.00	0.01	0.55
Yaw angle fluctuation (degrees)	14.93	15.36	0.43	0.41	2.80

Table AP. 4: Accuracy of 25Hz digitising in front crawl (Differences between 25Hz and 50Hz digitising in 5 different front crawl trials).

Variables (Front crawl)	50Hz Mean	25Hz Mean	Mean difference	SD of the difference	difference (%)
Stroke length (m·cycle ⁻¹)	2.25	2.25	0.00	0.04	0.11
Cycle Time (s)	1.37	1.37	0.00	0.01	0.11
Stroke frequency (cycles·min ⁻¹)	44.79	44.14	-0.64	0.89	1.46
Stroke index (m ² ·cycle ⁻¹ ·s ⁻¹)	3.73	3.70	-0.03	0.05	0.80
Velocity of the centre of mass (m·s ⁻¹)	1.66	1.64	-0.02	0.04	1.02
Intra-cycle maximum velocity (m·s ⁻¹)	1.88	1.88	-0.01	0.06	0.39
Intra-cycle minimum velocity (m·s ⁻¹)	1.45	1.44	-0.01	0.10	0.74
Intra-cycle velocity variation (m·s ⁻¹)	0.44	0.44	0.00	0.07	0.75
Entry phase duration (s)	0.48	0.46	-0.02	0.01	3.30
Pull phase duration (s)	0.18	0.19	0.01	0.02	3.99
Push phase duration (s)	0.24	0.25	0.01	0.01	2.41
Release phase duration (s)	0.06	0.06	0.00	0.00	1.02
Above-water phase duration (s)	0.41	0.41	0.00	0.01	0.91
Propulsive phase duration (s)	0.43	0.44	0.01	0.01	2.64
Non-propulsive phase duration (s)	0.94	0.93	-0.01	0.01	1.08
Shoulder roll angle (degrees)	52.43	53.29	-0.85	1.37	1.60
Hip roll angle (degrees)	40.36	39.03	1.33	0.64	3.40
Hand speed during the pull phase (m·s ⁻¹)	-0.98	-0.99	-0.01	0.03	0.94
Hand speed during the push phase (m·s ⁻¹)	-1.10	-1.11	-0.01	0.04	1.19
Mean hand speed during the underwater phases in the vertical direction (m·s ⁻²)	1.16	1.20	0.03	0.02	2.69
Mean hand speed during the underwater phases in the lateral direction (m·s ⁻²)	0.56	0.58	0.02	0.03	3.54
Hand acceleration during the pull phase (m·s ⁻²)	-6.80	-7.04	-0.24	0.28	3.42
Hand acceleration during the push phase (m·s ⁻²)	4.22	4.24	0.02	0.21	0.44
Total 3D hand path distance (m)	3.61	3.60	-0.01	0.04	0.15
Entry phase 3D hand path distance (m)	0.55	0.55	0.00	0.03	0.17
Pull phase 3D hand path distance (m)	0.62	0.61	-0.02	0.00	2.31
Push phase 3D hand path distance (m)	0.80	0.80	0.00	0.03	0.48
Release phase 3D hand path distance (m)	0.22	0.22	0.00	0.02	2.03
Above-water phase 3D hand path distance (m)	1.61	1.61	0.01	0.02	0.32
Total 3D foot path distance (m)	2.07	2.10	0.02	0.03	1.09
3D hand speed (m·s ⁻¹)	2.64	2.64	-0.01	0.03	0.35
3D foot speed (m·s ⁻¹)	1.51	1.53	0.02	0.03	1.00
Range of motion of the foot in the vertical direction (m)	0.47	0.47	0.00	0.01	1.06
Range of motion of the foot in the lateral direction (m)	0.19	0.18	0.00	0.01	1.65
Mean shoulder horizontal abduction angle during the pull phase (degrees)	169.10	168.47	-0.63	1.20	0.37
Mean shoulder horizontal abduction angle during the push phase (degrees)	157.47	154.48	-3.00	2.48	1.94
Mean elbow angle during the pull phase (degrees)	135.75	137.73	1.99	3.93	1.44
Mean elbow angle during the push phase (degrees)	120.11	119.10	-1.01	1.40	0.84
Net impulse (Ns) during the propulsive phase	9.81	10.41	0.60	1.48	5.72
Maximum lateral distance between the hand and COM (m)	0.34	0.34	0.00	0.01	0.02
COM maximum vertical displacement (m)	-0.12	-0.11	0.00	0.00	1.14
COM minimum vertical displacement (m)	-0.17	-0.17	0.00	0.00	1.18
COM mean vertical displacement (m)	-0.14	-0.14	0.00	0.00	1.04
Shoulder mean vertical displacement (m)	-0.06	-0.06	0.00	0.00	3.10
Hip mean vertical displacement (m)	-0.20	-0.20	0.00	0.00	0.36
Knee minimum vertical displacement (m)	-0.30	-0.30	0.00	0.00	0.54
Knee mean vertical displacement (m)	-0.23	-0.23	0.00	0.00	0.80
Foot minimum vertical displacement (m)	-0.35	-0.35	0.00	0.01	0.05
Foot mean vertical displacement (m)	-0.18	-0.17	0.00	0.00	1.92
Contribution of the entry phase on the 3D hand speed	0.41	0.40	-0.01	0.00	2.33
Contribution of the pull phase on the 3D hand speed	0.46	0.44	-0.03	0.01	3.75
Contribution of the push phase on the 3D hand speed	0.60	0.59	-0.02	0.01	3.33
Contribution of the release phase on the 3D hand speed	0.17	0.16	0.00	0.02	4.03
Contribution of the above-water phase on the 3D hand speed	1.19	1.18	-0.04	0.02	0.95
Timing index (%)	67.26	67.64	0.38	0.61	0.56
Froude efficiency (%)	0.63	0.62	0.00	0.01	0.71
Yaw angle fluctuation (degrees)	10.66	10.92	0.26	0.87	2.39

Table AP. 5: Testing speeds for Study 1, Study 2, and Study 3.

Participant	Study 1 (1×300m)	Study 2 (4×50m)								Study 3 (4×50m)			
	Front crawl & Back crawl	Back crawl				Front crawl				Front crawl & Back crawl			
1	1.03	1.33	1.43	1.51	1.61	1.52	1.64	1.74	1.85	1.33	1.43	1.51	1.61
2	1.01	1.28	1.38	1.46	1.56	1.49	1.60	1.70	1.81	1.28	1.38	1.46	1.56
3	1.03	1.25	1.34	1.43	1.52	1.52	1.64	1.74	1.85	1.25	1.34	1.43	1.52
4	1.02	1.30	1.39	1.48	1.57	1.36	1.46	1.55	1.65	1.30	1.39	1.48	1.57
5	1.01	1.22	1.32	1.40	1.49	1.39	1.50	1.59	1.69	1.22	1.32	1.40	1.49
6	1.05	1.32	1.41	1.50	1.60	1.40	1.50	1.59	1.70	1.32	1.41	1.50	1.60
7	1.12	1.36	1.47	1.56	1.66	1.41	1.52	1.61	1.72	1.36	1.47	1.56	1.66
8	1.04	1.23	1.33	1.41	1.50	1.37	1.47	1.56	1.66	1.23	1.33	1.41	1.50
9	1.08	1.43	1.53	1.63	1.73	1.50	1.62	1.72	1.83	1.43	1.53	1.63	1.73
10	1.04	1.32	1.42	1.51	1.61	1.46	1.57	1.67	1.78	1.32	1.42	1.51	1.61
Mean	1.04	1.30	1.40	1.49	1.58	1.44	1.55	1.65	1.75	1.30	1.40	1.49	1.58
SD	0.04	0.06	0.07	0.07	0.08	0.06	0.07	0.07	0.08	0.06	0.07	0.07	0.08

Table AP. 6: Results from post-hoc tests for variables in back crawl on which main effects of the trial were observed. a, b, c, d mean the significant differences ($p < 0.05$) from trial-1, trial-2, trial-3, trial-4 respectively.

Variables (Back crawl)	Trial-1	Trial-2	Trial-3	Trial-4
COM speed ($m \cdot s^{-1}$)	1.25±0.10 ^{b,c,d}	1.34±0.09 ^{a,c,d}	1.41±0.09 ^{a,b,d}	1.54±0.06 ^{a,b,c}
SF ($cycles \cdot min^{-1}$)	30.44±4.63 ^{b,c,d}	33.24±3.73 ^{a,c,d}	37.53±5.31 ^{a,b,d}	44.81±4.68 ^{a,b,c}
SL ($m \cdot cycles^{-1}$)	2.48±0.22 ^{c,d}	2.44±0.20 ^{c,d}	2.28±0.22 ^{a,b,d}	2.07±0.17 ^{a,b,c}
Pull phase relative duration (%)	11.73±1.37 ^{c,d}	12.35±1.18 ^d	13.05±1.25 ^{a,d}	15.19±2.00 ^{a,b,c}
Push phase relative duration (%)	12.52±1.51 ^d	13.20±1.20 ^d	14.56±1.56	16.10±2.72 ^{a,b}
Above-water phase relative duration (%)	35.31±2.81 ^d	35.39±2.89 ^d	34.75±2.57 ^d	33.21±1.43 ^{a,b,c}
IV _{max} ($m \cdot s^{-1}$)	1.45±0.13 ^{b,c,d}	1.54±0.11 ^{a,d}	1.62±0.10 ^{a,d}	1.76±0.08 ^{a,b,c}
IV _{min} ($m \cdot s^{-1}$)	1.06±0.15 ^{b,c,d}	1.15±0.13 ^{a,c,d}	1.20±0.10 ^{a,b,d}	1.30±0.08 ^{a,b,c}
Mean hand acceleration in the swimming direction during the pull phase ($m \cdot s^{-2}$)	8.61±1.57	9.22±1.05	9.80±2.08	10.75±1.74
Mean hand acceleration in the swimming direction during the push phase ($m \cdot s^{-2}$)	-7.21±1.25 ^d	-7.74±1.02 ^d	-8.69±2.10	-9.85±1.88 ^{a,b}
Mean hand speed during the underwater phases in the vertical direction ($m \cdot s^{-2}$)	0.86±0.14 ^d	0.91±0.15 ^d	0.92±0.16 ^d	1.08±0.13 ^{a,b,c}
Mean hand speed during the underwater phases in the lateral direction ($m \cdot s^{-2}$)	0.73±0.07 ^{c,d}	0.78±0.09 ^{c,d}	0.87±0.10 ^{a,b,d}	0.98±0.09 ^{a,b,c}
3D hand speed ($m \cdot s^{-1}$)	2.23±0.30 ^{b,c,d}	2.45±0.26 ^{a,c,d}	2.73±0.32 ^{a,b,c}	3.20±0.20 ^{a,b,c}
Froude efficiency	0.56±0.04 ^{c,d}	0.55±0.04 ^{c,d}	0.52±0.03 ^{a,b,d}	0.48±0.03 ^{a,b,c}
3D Hand Path Distance (m)	2.47±0.12	2.43±0.10	2.38±0.09	2.33±0.17
Mean COM vertical displacement (m)	-0.17±0.02 ^{c,d}	-0.17±0.02 ^d	-0.16±0.02 ^{a,d}	-0.16±0.01 ^{a,b,c}
Mean COM vertical displacement (m)	-0.16±0.02 ^{c,d}	-0.15±0.02 ^{c,d}	-0.15±0.02 ^{a,b}	-0.14±0.01 ^{a,b}
Mean COM vertical displacement (m)	-0.19±0.02 ^d	-0.19±0.02 ^d	-0.19±0.02	-0.18±0.02 ^{a,b}
Mean foot vertical displacement (m)	-0.32±0.04 ^{a,d}	-0.31±0.03 ^a	-0.31±0.04 ^d	-0.30±0.04 ^{a,c}
Minimum foot vertical displacement (m)	-0.01±0.05 ^d	0.00±0.06	0.01±0.04	0.09±0.05 ^a
Mean knee vertical displacement (m)	-0.23±0.02 ^{c,d}	-0.22±0.02 ^d	-0.21±0.02 ^{a,d}	-0.20±0.02 ^{a,b,c}
Minimum knee vertical displacement (m)	-0.35±0.04 ^d	-0.34±0.03 ^d	-0.33±0.03 ^d	-0.31±0.03 ^{a,b,c}
Mean elbow joint angle during the push phase (degrees)	116.19±8.36 ^{c,d}	116.45±7.10 ^{c,d}	122.04±10.07 ^{a,b}	125.75±12.38 ^{a,b}
Maximum elbow joint angle during the push phase (degrees)	146.21±10.60	142.16±6.34 ^{c,d}	149.74±8.30 ^b	152.41±12.97 ^b
Minimum elbow joint angle during the push phase (degrees)	100.51±8.12 ^{b,c,d}	103.00±7.88 ^{a,c,d}	107.24±10.68 ^{a,b}	108.62±10.52 ^{a,b}

Table AP. 7: Results from post-hoc tests for variables in front crawl on which main effects of the trial were observed. a, b, c, d mean the significant differences ($p < 0.05$) from trial-1, trial-2, trial-3, trial-4 respectively.

Variables (Front crawl)	Trial-1	Trial-2	Trial-3	Trial-4
COM speed ($\text{m}\cdot\text{s}^{-1}$)	1.43±0.13 ^{b,c,d}	1.52±0.13 ^{a,c,d}	1.60±0.14 ^{a,b}	1.70±0.04 ^{a,b}
SF ($\text{cycles}\cdot\text{min}^{-1}$)	34.11±5.01 ^{b,c,d}	39.40±6.94 ^{a,c,d}	43.74±8.76 ^{a,b,d}	51.67±6.38 ^{a,b,c}
SL ($\text{m}\cdot\text{cycles}^{-1}$)	2.54±0.24 ^{b,c,d}	2.35±0.29 ^{a,c,d}	2.25±0.30 ^{a,b,d}	2.00±0.25 ^{a,b,c}
Entry phase relative duration (%)	39.25±7.40 ^{b,c,d}	35.94±7.29 ^{a,d}	33.45±6.61 ^{a,d}	29.36±4.07 ^{a,b,c}
Pull phase relative duration (%)	12.63±2.16 ^{b,c,d}	13.98±2.20 ^{a,c,d}	15.90±2.52 ^{a,b,d}	17.71±1.78 ^{a,b,c}
Push phase relative duration (%)	15.37±2.53 ^{b,d}	17.11±3.09 ^a	16.67±2.16 ^d	18.64±1.61 ^{a,c}
IVV ($\text{m}\cdot\text{s}^{-1}$)	0.34±0.06	0.36±0.07	0.39±0.10	0.42±0.18
IV _{max} ($\text{m}\cdot\text{s}^{-1}$)	1.62±0.12 ^{b,c,d}	1.70±0.12 ^{a,c,d}	1.81±0.17 ^{a,b}	1.89±0.10 ^{a,b}
IV _{min} ($\text{m}\cdot\text{s}^{-1}$)	1.28±0.14 ^{b,c,d}	1.38±0.13 ^{a,c,d}	1.42±0.13 ^{a,b}	1.50±0.10 ^{a,b}
Maximum shoulder roll angle (degrees)	63.01±6.34 ^{c,d}	56.62±8.27	55.31±7.87 ^a	52.88±4.89 ^a
Maximum hip roll angle (degrees)	51.92±11.26 ^{c,d}	45.73±11.76 ^d	42.35±11.23 ^a	33.79±6.07 ^{a,b}
Mean hand speed in the swimming direction during the push phase ($\text{m}\cdot\text{s}^{-1}$)	1.12±0.14 ^{b,c,d}	1.18±0.15 ^{a,c,d}	1.26±0.15 ^{a,b}	1.34±0.18 ^{a,b}
Mean hand acceleration in the swimming direction during the pull phase ($\text{m}\cdot\text{s}^{-2}$)	6.17±1.59 ^{b,c,d}	7.52±1.12 ^a	7.50±1.43 ^a	8.35±1.07 ^a
Mean hand acceleration in the swimming direction during the push phase ($\text{m}\cdot\text{s}^{-2}$)	-5.25±1.03 ^c	-5.57±0.59	-6.33±1.41 ^a	-6.49±0.99
3D hand speed ($\text{m}\cdot\text{s}^{-1}$)	2.16±0.33 ^{b,c,d}	2.55±0.47 ^{a,c,d}	2.76±0.54 ^{a,b,c}	3.20±0.40 ^{a,b,c}
3D Hand Path Distance (m)	2.29±0.16	2.32±0.09 ^d	2.26±0.14	2.20±0.12 ^b
Mean COM vertical displacement (m)	-0.15±0.02	-0.15±0.02	-0.14±0.03	-0.14±0.01
Minimum COM vertical displacement (m)	-0.18±0.03 ^d	-0.18±0.04	-0.18±0.04	-0.16±0.02 ^a

Table AP. 8: Results from post-hoc tests for variables in front crawl at back crawl speeds on which main effects of the trial were observed. a, b, c, d mean the significant differences ($p<0.05$) from trial-1, trial-2, trial-3, trial-4 respectively.

Variables (Front crawl at back crawl speeds)	Trial-1	Trial-2	Trial-3	Trial-4
COM speed ($\text{m}\cdot\text{s}^{-1}$)	1.28±0.09 ^{b,c,d}	1.38±0.07 ^{a,c,d}	1.45±0.09 ^{a,b,d}	1.56±0.09 ^{a,b,c}
SF ($\text{cycles}\cdot\text{min}^{-1}$)	29.38±3.08 ^{b,c,d}	31.34±3.79 ^{a,c,d}	34.64±5.17 ^{a,b,d}	42.67±4.68 ^{a,b,c}
SL ($\text{m}\cdot\text{cycles}^{-1}$)	2.48±0.22 ^{b,c,d}	2.44±0.20 ^{a,c,d}	2.28±0.22 ^{a,b,d}	2.07±0.17 ^{a,b,c}
SI ($\text{m}^2\cdot\text{cycles}^{-1}\cdot\text{s}^{-1}$)	3.37±0.34 ^{b,c}	3.64±0.27 ^{a,d}	3.68±0.27 ^{a,d}	3.46±0.21 ^{b,c}
Entry phase relative duration (%)	44.76±3.50 ^{b,d}	41.39±6.32 ^{a,d}	40.79±5.56 ^{a,d}	34.63±4.55 ^{a,b,c}
Pull phase relative duration (%)	11.67±1.46 ^d	11.68±1.35 ^{c,d}	12.65±1.82 ^{b,d}	14.43±1.76 ^{a,b,c}
Push phase relative duration (%)	13.23±1.13 ^{c,d}	15.83±4.17	15.76±1.61 ^{a,d}	17.68±2.15 ^{a,c}
Above-water phase relative duration (%)	24.67±3.10 ^{c,d}	25.38±3.75 ^d	25.65±3.38 ^{a,d}	27.23±3.11 ^{a,b,c}
IV_{\max} ($\text{m}\cdot\text{s}^{-1}$)	1.46±0.09 ^{b,c,d}	1.58±0.09 ^{a,d}	1.61±0.07 ^{a,d}	1.80±0.13 ^{a,b,c}
IV_{\min} ($\text{m}\cdot\text{s}^{-1}$)	1.10±0.08 ^{b,c,d}	1.21±0.09 ^{a,c,d}	1.28±0.10 ^{a,b,d}	1.41±0.11 ^{a,b,c}
Maximum shoulder roll angle (degrees)	65.93±4.48 ^d	62.42±4.89 ^d	59.39±6.61	56.73±5.09 ^{a,b}
Maximum hip roll angle (degrees)	61.98±6.07 ^d	56.07±7.36 ^d	51.88±9.54 ^d	42.30±6.41 ^{a,b,c}
Mean hand acceleration in the swimming direction during the pull phase ($\text{m}\cdot\text{s}^{-2}$)	5.94±2.08 ^{c,d}	6.73±1.88	7.60±1.21 ^a	7.38±2.00 ^a
Mean hand acceleration in the swimming direction during the push phase ($\text{m}\cdot\text{s}^{-2}$)	-4.83±0.88 ^{c,d}	-5.11±0.70 ^{c,d}	-5.90±0.83 ^{a,b}	-6.62±1.16 ^{a,b}
Mean hand speed during the underwater phases in the vertical direction ($\text{m}\cdot\text{s}^{-2}$)	0.80±0.10 ^{b,c,d}	0.90±0.15 ^{a,d}	0.95±0.15 ^{a,d}	1.16±0.14 ^{a,b,c}
Mean hand speed during the underwater phases in the lateral direction ($\text{m}\cdot\text{s}^{-2}$)	0.37±0.06 ^{b,c,d}	0.43±0.09 ^{a,d}	0.46±0.10 ^{a,d}	0.55±0.10 ^{a,b,c}
3D hand speed ($\text{m}\cdot\text{s}^{-1}$)	1.83±0.20 ^{b,c,d}	2.04±0.31 ^{a,c,d}	2.23±0.31 ^{a,b,c}	2.69±0.30 ^{a,b,c}
Froude efficiency	0.70±0.04 ^d	0.68±0.07 ^d	0.66±0.06 ^d	0.59±0.05 ^{a,b,c}
3D Hand Path Distance (m)	2.40±0.15 ^{c,d}	2.35±0.07 ^d	2.34±0.12 ^{a,d}	2.24±0.12 ^{a,b,c}
Mean COM vertical displacement (m)	-0.16±0.02 ^d	-0.15±0.02 ^d	-0.15±0.02 ^d	-0.14±0.02 ^{a,b,c}
Mean COM vertical displacement (m)	-0.13±0.01 ^d	-0.13±0.02 ^d	-0.12±0.02	-0.11±0.02 ^{a,b}
Mean COM vertical displacement (m)	-0.20±0.03 ^{c,d}	-0.19±0.03	-0.18±0.03 ^a	-0.18±0.03 ^a
Mean foot vertical displacement (m)	-0.22±0.03 ^d	-0.21±0.03 ^d	-0.21±0.03 ^d	-0.19±0.03 ^{a,b,c}
Mean knee vertical displacement (m)	-0.24±0.03 ^d	-0.23±0.03	-0.23±0.04	-0.22±0.04 ^a
Minimum knee vertical displacement (m)	-0.35±0.06 ^d	-0.34±0.05 ^d	-0.34±0.06 ^d	-0.31±0.05 ^{a,b,c}