BIOMECHANICAL CHARACTERISTICS OF HIGHLY-TRAINED SINGLE-ARM AMPUTEE FRONT CRAWL SWIMMERS

By

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ABSTRACT

The general aim of this thesis was to contribute to the body of scientific knowledge regarding the biomechanical characteristics of highly-trained single-arm amputee front crawl swimmers, thus allowing for the application of this knowledge to enhance swimming performance. With this in mind, five experimental studies were undertaken, which focused on three main areas: Firstly, how swimmers adjusted their stroke parameters in order to swim faster and which of the swimmers' anthropometric characteristics were related to performance. Secondly, what inter-arm and leg-to-arm coordination patterns were exhibited by these swimmers and how inter-limb coordination was related to the attainment of maximum swimming speed. Thirdly, what three-dimensional arm movements were used by these swimmers during the front crawl stroke cycle and how these movements contributed to propulsion and as a consequence the overall progression of the swimmers through the water.

The findings of this thesis suggest that when single-arm front crawl swimmers are sprinting: (a) the attainment of a high stroke frequency is more important than swimming with the longest possible stroke; (b) reducing the length of time the affected-arm is held stationary in front of the body will help attain a high stroke frequency; (c) the rhythmical alignment of leg kicks to arm strokes may enhance performance and contribute to the stability of inter-arm coordination; (d) amputees use a more linear underwater hand movement, than able-bodied swimmers and use one of three distinct movement patterns to pull their affected-arm through the water; (e) increases in intra-cyclic swimming velocity can be achieved with the unaffected-arm, but not so with the affected-arm. The findings of this thesis will be of interest to scientists working in the area of swimming biomechanics. They should also be of some practical benefit to unilateral arm-amputee front crawl swimmers and to those who coach and teach them.

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RESEARCH OUTPUTS FROM THE THESIS

At the time of submission, the following research outputs have arisen from the thesis:

Articles published in peer-reviewed journals:

Osborough, C., Payton, C., & Daly. D (2010). Influence of swimming speed on inter-arm coordination in competitive unilateral arm amputee front crawl swimmers. *Human Movement Science*, *29*, 921-931.

Osborough, C., Payton, C., & Daly, D. (2009). Relationships between the front crawl stroke parameters of competitive unilateral arm amputee swimmers, with selected anthropometric characteristics. *Journal of Applied Biomechanics, 25*(4), 304-312.

Peer-reviewed papers, presented at international conferences and symposia:

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Osborough, C., Payton, C., & Daly. D. (2012). Influence of swimming speed on leg-to-arm coordination in competitive unilateral arm amputee front crawl swimmers. *International Convention on Science, Education and Medicine in Sport* (19th – 24th July 2012). Accepted 14th February 2012.

Osborough, C., Payton, C., & Daly. D. (2010). Influence of swimming speed on the affected- and affected-arm stroke phases of competitive unilateral arm amputee front crawl swimmers. In P.-L. Kjendlie, R.K. Stallman, J. Cabri (Eds.), *Biomechanics and Medicine in Swimming XI* (pp140-142). Norwegian School of Sport Science, Olso.

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CHAPTER ONE

AN INTRODUCTION TO DISABILITY SWIMMING AND FRONT CRAWL PERFORMANCE

This chapter provides a short historical background to disability swimming, explaining how it came into being and how it evolved from inception to its current highly competitive form. This chapter also briefly explains the classification process for swimmers with a disability, describes the front crawl stroke and identifies the biomechanical factors that limit front crawl performance.

1.1 Disability swimming

The origins of competitive disability swimming date back to 1948, when Sir Ludwig Guttmann organised a sports competition involving World War II veterans with spinal cord injuries in Stoke Mandeville, England. Swimming was then included in the first Olympic style games for athletes with a disability in Rome in 1960, where 400 athletes from 23 countries took part across a range of sports. Today, the most important competition for athletes with a disability is the Paralympic Games, within which swimming is an integral part. The Paralympic Games, which focuses on elite performances rather than on the athletes' disability, has now evolved into a major sports event second only to the Olympic Games. Indeed, at the 2008 Beijing Games the number of participating athletes was 3,951 (Figure 1.1), from 146 countries (Figure 1.2) competing in 20 sports. The Paralympic Games are held in the same year as the Olympic Games and since 1988 they have also taken place at the same Olympic venue (International Paralympic Committee, 2011[a]).

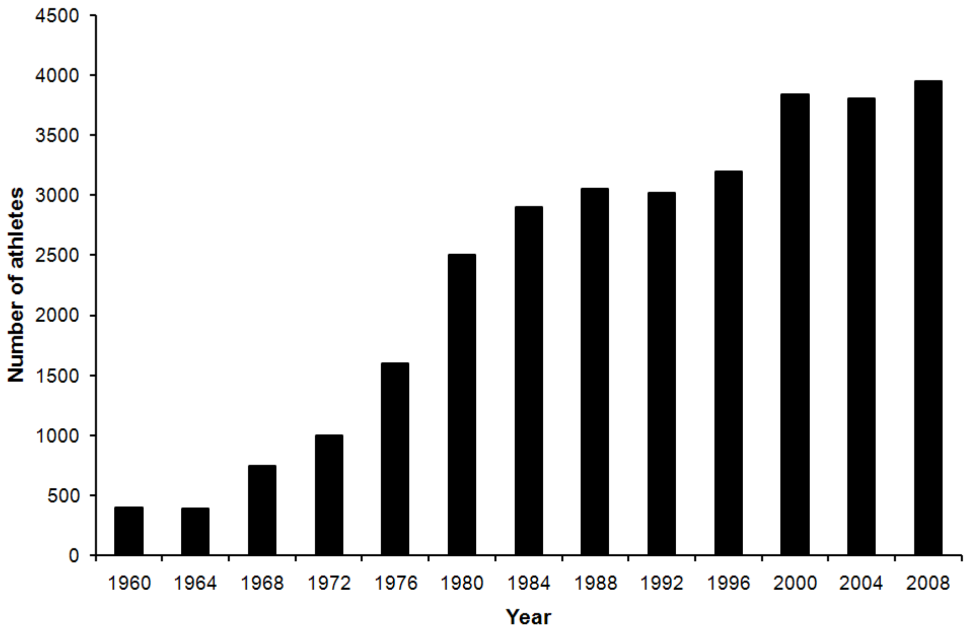


Figure 1.1. Evolution in the numbers of participating athletes from the 1960 to the 2008 Paralympic Games (International Paralympic Committee, 2011[a]).

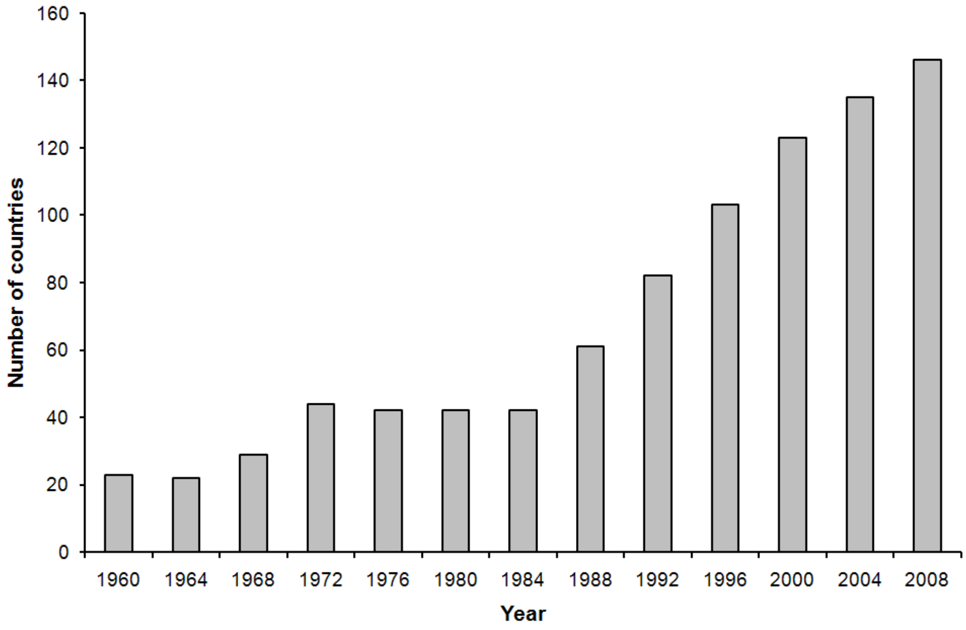


Figure 1.2. Evolution in the numbers of participating countries from the 1960 to the 2008 Paralympic Games (International Paralympic Committee, 2011[a]).

Since the first Paralympic Games in Rome in 1960, swimming has been one of the main sports of the Paralympics. Swimmers compete in front crawl, backstroke, breaststroke, butterfly and individual medley events, in distances ranging from 50 m to 400 m. At the 2008 Beijing Games, 560 swimmers from more than 80 countries competed in 140 swimming events, while in the 2012 London Games, 600 swimmers will compete in 148 events. These swimming events are governed by the International Paralympic Committee (IPC) Swimming Technical Committee, which incorporates the rules of the International Swimming Federation (FINA). These rules are followed with a few modifications, such as optional platform or in-water starts for some races and the use of signals or "tappers" for swimmers with blindness or visual impairment. However, unlike other Paralympic sports (e.g., athletics and cycling), no prostheses or assistive devices are permitted in swimming (International Paralympic Committee, 2011[b]).

1.2 International Paralympic Committee classification

The distinguishing factor in Paralympic sport is classification. Classification aims to confirm the eligibility of competitors and group individuals of like potential into classes for competition in a valid manner. Within Paralympic sport, six different disability groups are recognised. They are: 1) Amputee; 2) Cerebral palsy; 3) Spinal cord injury; 4) Visual impairment; 5) Intellectual disability; and 6) Les autres (includes conditions which do not fit into any of the other five groups). Before 1992, swimmers competed against those with the same disability. For example, all swimmers with cerebral palsy raced against each other regardless of the severity of their disability. However, since the 1992 Barcelona Paralympics swimmers with a disability are now classed according to their functional ability rather than their disability. Thus, the current classification system attempts to predict swimming performance based on physical potential.

The IPC classification system (International Paralympic Committee, 2011[c]) consists of a functional assessment on dry-land (bench test), a water-based assessment and observation of the swimmer during competition. Swimmers receive a point score from these tests, which are conducted by at least one medical and one swimming technical classifier.

The dry-land assessment is performed in a horizontal position on a medical testing bench and includes one or a combination of the following tests:

1. Muscular strength
2. Joint coordination
3. Joint mobility
4. Measurement of amputation(s)
5. Measurement of the trunk
6. Drop shoulder test (for relevant swimmers)

Swimmers then perform the water-based assessment in which aspects, such as start, turn and stroking techniques, are examined. Points are awarded based on the swimmer's ability to execute these techniques, according to the following breakdown:

Arms	130 points	Starts	10 points
Legs	100 points	Turns	10 points
Trunk	50 points		

Swimmers are then observed during competition to validate their performances during the dry-land and water-based assessments. The accumulated point score from these tests (to a maximum of 300 points) is then used to determine the class within which the swimmer competes. In front crawl, swimmers with various loco-motor disabilities are grouped into one of ten classes where the higher the S class number, the more functional the swimmer. For these swimmers, the classification scale ranges from S1 (40 – 60 points) to S10 (266 – 285 points). Swimmers with visual impairment are divided into three classes; S11, S12 and S13 based on visual acuity, visual field and light perception. S14 is the class organised for those with intellectual disability based on the results from a training history and sport limitation questionnaire, a battery of sport cognition tests and observation during competition.

1.3 Single-arm amputee swimmers

Swimmers with a single, elbow-level amputation compete in the IPC S9 Class (241 – 265 points) for front crawl. Within this class, these swimmers compete against others with various physical impairments (Table 1.1). For example, a swimmer with a single, through-elbow amputation might compete against a double below-knee amputee in the same race. According to the IPC classification regulations (2011[c]) swimmers with a single, elbow-level amputation have a practical profile as follows:

“HANDS: Able to catch the water gaining full propulsion in one hand only; ARMS: Full controlled arm cycle gaining full propulsion in one arm and satisfactory propulsion with the other arm; TRUNK: Full trunk control; LEGS: Full propulsive kick; STARTS: Standing start with full power off the starting platform; TURNS: Full power from push off at turns.”

Table 1.1. Disability profile for the IPC S9 Class in front crawl swimming (International Paralympic Committee, 2011[c]).

S9 Class		Disability Profile
1.	a)	Walking paraplegia with minimal involvement in limbs.
	b)	Polio with one non-functional leg.
2.		Slight overall functional coordination problems.
3.	a)	Single above knee amputation.
	b)	Single through knee amputation.
	c)	Double below knee amputation, stumps longer than 1/3.
	d)	Single through elbow amputation.
	e)	Single below elbow amputation.
4.		Partial joint restriction in the lower limbs, one side more affected.

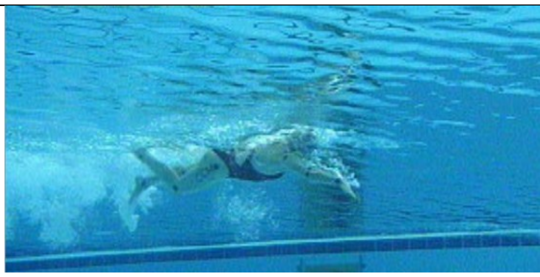
Being deprived of an important propelling surface (hand plus forearm segment) undoubtedly disadvantages a competitive swimmer with a single, elbow-level amputation, when compared to an able-bodied swimmer. Such a difference is clearly evident between the current World Records for the men’s able-bodied and S9 100 m front crawl. At the time of writing, the able-bodied 100 m front crawl World Record was held by Cesar Cielo from Brazil at 46.91 s, while the S9 100 m World Record was held by Matthew Cowdrey (a single, elbow-level amputee) from Australia at 55.20 s.

1.4 Front crawl swimming

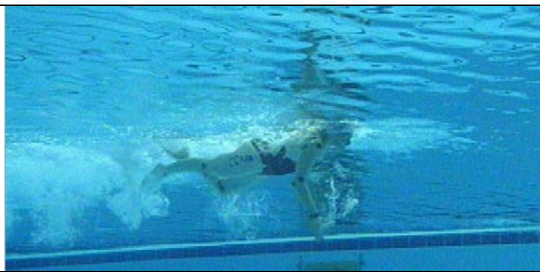
The front crawl technique consists of an alternating right and left arm stroke and a varying number of alternating kicks (Maglischo et al., 1988). Whilst underwater the hand follows an S-shaped pull pattern and upon exit is recovered over the water.

Glide.
The hand enters the water smoothly and is then stretched directly forward in a streamlined manner.

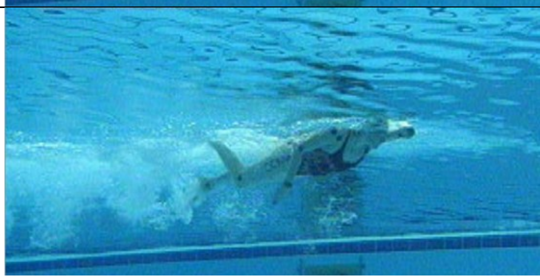
Downsweep.
The wrist flexes, initiating a downward movement of the hand which is swept down, out and forward in a curvilinear path.



Insweep.
The hand is swept back, in a semi-circular path from its widest point until it is underneath the swimmer's chest.



Upsweep.
The hand and arm is swept back, out and up from underneath the body towards the surface of the water.



Recovery.
As the hand exits the water it is brought forward, up over the water ready to commence the next stroke.

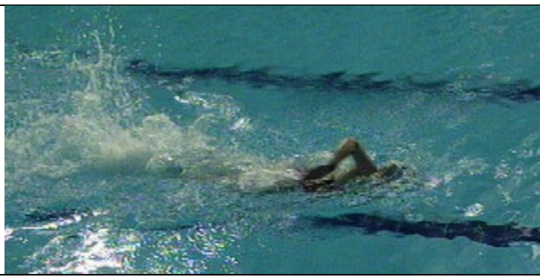


Figure 1.3. Different arm stroke phases in front crawl swimming. Phases taken from Maglischo (2003).

Traditionally, each arm stroke is divided into a number of distinct phases. Maglischo (2003) defined these phases as: Glide; Downsweep; Insweep; Upsweep and Recovery (Figure 1.3). During each stroke cycle swimmers kick typically using a six-, four- or two-beat rhythm. Each kick consists of an upbeat and a downbeat phase. Throughout the stroke cycle, swimmers maintain horizontal alignment while rolling about their longitudinal axis to either side. This bodyroll is coordinated with the alternating action of the right and left arm strokes. The rolling action of the trunk is believed to have several functions, including: facilitating breathing to the side (Payton, Bartlett, Baltzopolos, & Coombs, 1999), aiding arm recovery (Counsilman, 1968) and influencing the underwater medio-lateral hand movement pattern (S-shaped pull) (Payton, Bartlett, & Baltzopolos, 2002). To swim front crawl effectively, individuals must coordinate all of these complex body movements to maximise propulsion and minimise resistance.

1.5 Biomechanical factors limiting front crawl performance

The performance of a swimmer in a race depends on the time it takes him or her to complete the event distance. The major component of this "event time" is the time spent stroking and the amount of "stroking time" depends on the speed of the swimmer (Grimston & Hay, 1986). A swimmer's speed (v) is the product of their stroke length and stroke frequency (Craig & Pendergast, 1979; Hay, 2002):

$$v = SL \times SF \qquad [1]$$

where SL is the distance covered during one stroke cycle and SF is the number of stroke cycles per second. Stroke frequency is the reciprocal of the stroke time period (T_s):

$$SF = {}^{1}\!/_{T_s} \qquad [2]$$

which may be considered to be governed by the range of motion at the shoulder joint (θ_s) and the mean angular velocity of the humerus over that range (ω_s):

$$T_s = {}^{\theta_s}/_{\omega_s} \quad [3]$$

Stroke length can be considered to be a function of the horizontal forces acting on the swimmer (Grimston & Hay, 1986):

$$SL = f\,(\Sigma F_h) \quad [4]$$

which can be assessed using Newton's Second Law:

$$\Sigma F_h = m \times a \quad [5]$$

which becomes:

$$F_p - F_d = m \times a \quad [6]$$

where ΣF_h represents the sum of the horizontal forces acting, F_p is the propulsive force, F_d is the resistive force, m is the swimmer's mass, and a is his or her acceleration (Toussaint & Beek, 1992). At a constant swimming speed (a = 0) the propulsive force (forward directed force) is equal in magnitude, but opposite in direction, to the resistive force (that which opposes the swimmer's forward progression). Propulsive force (F_p) is considered to have both lift (L) and drag (D) components:

$$L = {}^{1}/_{2}\rho u^2 C_l A \quad [7]$$

$$D = {}^{1}/_{2}\rho u^2 C_d A \quad [8]$$

where u is the velocity of the swimmer's limb segments relative to the water, A is a representative area (e.g., surface area), ρ is the density of water and C_l and C_d are the lift and drag coefficients, respectively (Toussaint & Beek, 1992; Toussaint & Truijens, 2005). Resistive force (F_d) is determined by Pressure drag (F_{pd}), Wave drag (F_w) and Friction drag (F_f) components (Toussaint & Beek, 1992; Toussaint & Truijens, 2005). Hence:

$$F_d = F_{pd} + F_w + F_f \quad [9]$$

although this is often simplified to:

$$F_d = K \times v^2 \quad [10]$$

where K is a constant (drag factor) and v is the swimmer's speed (Toussaint, Roos, & Kolmogorov, 2004).

Solely considering the horizontal forces acting however, ignores the fact that to generate propulsion, some of the swimmer's total mechanical power (P_o) must be used giving water a kinetic energy change (P_k), since the propelling thrust is made against masses of water that acquire a backward momentum, rather than a fixed point (Toussaint & Beek, 1992). The remainder therefore, equals the power (P_d) needed by the swimmer to overcome the drag force. Thus:

$$P_o = P_d + P_k \qquad [11]$$

where:

$$P_d = F_d \times v \qquad [12]$$

and:

$$P_k = {}^{1}/_{2}\ \Sigma m_w\ (\Delta v_w)^2\ SF \qquad [13]$$

where Σm_w is the mass of pushed away water, Δv_w is its velocity change and SF is the swimmer's stroke frequency. As outlined by Toussaint and Beek (1992), the ratio between the useful mechanical power (P_d) and the total mechanical power (P_o) is defined as propelling efficiency (e_p):

$$e_p = {}^{P_d}/_{P_o} = {}^{P_d}/_{(P_d + P_k)} \qquad [14]$$

which is related to the surface area of the swimmer's propelling limbs (e.g., hand) by:

$$e_p = \frac{1}{1 + \sqrt{\frac{C_{db} \times A_b}{C_h \times A_h}}} \qquad [15]$$

where C_{db} and C_h are the drag coefficients of the body and hand, respectively and A_b and A_h are the frontal area of the whole body and the hand's surface area, respectively (Toussaint & Beek, 1992).

A swimmer with a high propelling efficiency (i.e., someone who transfers less kinetic energy to the water) would be expected to have a longer stroke length as a consequence of a more effective force application, when compared to a swimmer with a low propelling efficiency, given that:

$$SL = \left(e_p \times W_o\right)/F_d \qquad [16]$$

where W_o is the total work done per stroke (Toussaint & Beek, 1992). Thus, attributes such as large muscles (e.g., those found in the upper region of the torso) to generate large forces and large propelling surfaces (e.g., hand surface area) combined with a swimming technique that minimises drag force and maximises propelling efficiency (e.g., reduces slippage; the backward displacement of the hand relative to the water), are beneficial to swimming performance.

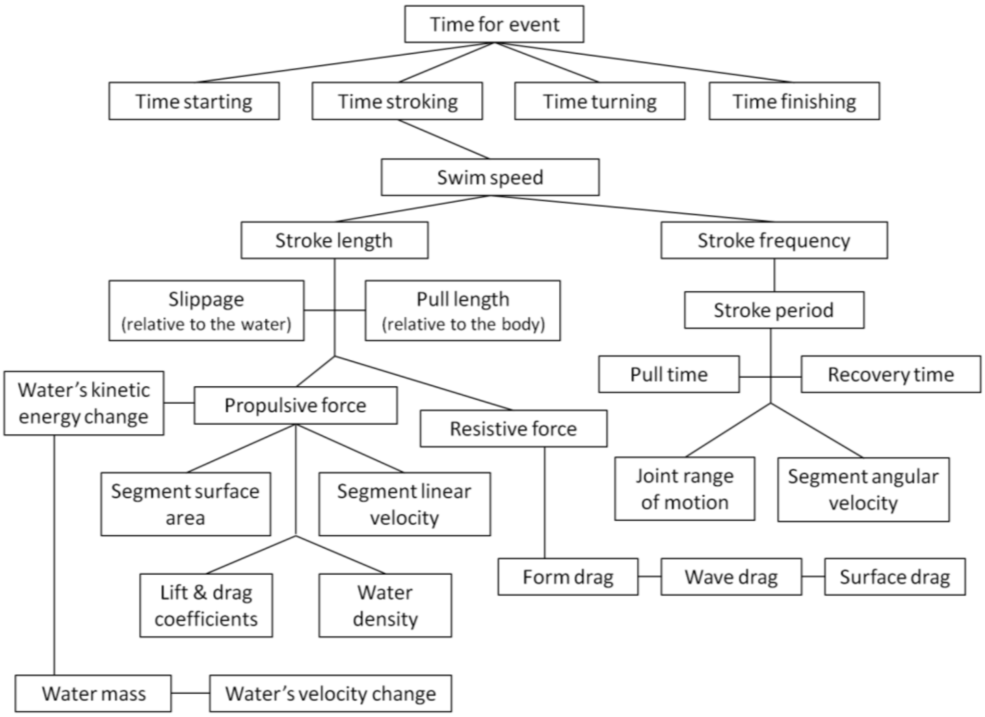


Figure 1.4. Theoretical model identifying the biomechanical factors that limit front crawl performance. This model relates to the structure of the thesis.

Within each stroke cycle however, swimming speed is not constant ($a \neq 0$) as both propulsion and resistance fluctuate. Such changes in swimming speed result in an additional work demand of the swimmer (Nigg, 1983). Thus, an understanding of the interplay between the horizontal forces acting is crucial when evaluating the effectiveness and economy of a swimmer's technique.

By utilising a theoretical model of technical performance (Figure 1.4) the critical biomechanical factors that limit front crawl performance can be identified. This thesis uses the theoretical model outlined in Figure 1.4 to systematically examine the biomechanical characteristics of highly-trained single-arm amputee front crawl swimmers. The literature pertaining to the biomechanical characteristics of front crawl swimming, in general, will be reviewed in the following chapter.

1.6 Structure of the thesis

The remainder of this thesis comprises of seven chapters: a review of literature, five experimental studies and a summary, applications and recommendations section. For the five experimental studies, the majority of data collection took place at the Centre for Aquatics Research and Education (University of Edinburgh), using mostly the same participants (Appendix 1). To date, two chapters (Studies 1 and 2) have been published as scientific journal manuscripts.

1.6.1 Chapter 2 – Literature Review

The aim of this chapter is to provide an extensive review of the literature on the biomechanical characteristics of front crawl swimmers. Where possible, research related to swimmers with a physical impairment will be highlighted. However, the number of published studies in this area is limited. Within the review, established biomechanical data collection techniques are also identified and discussed. This review enabled the identification of aspects of the front crawl stroke, specific to single-arm amputees, that were worthy of study. The specific topics that were researched and the academic aims of the thesis are stated at the end of this chapter.

1.6.2 Chapter 3 – Study 1

This chapter determines how, in order to compensate for their missing limb, single-arm amputee swimmers rely on the relative combinations of stroke length and stroke frequency to swim front crawl over a range of speeds. This chapter also assesses which stroking parameters and anthropometric characteristics of these swimmers are important for successful swimming performance. Chapter 3 relates to academic aim 1, in Section 2.13.

1.6.3 Chapter 4 – Study 2

This chapter examines whether the inter-arm coordination of single-arm amputees changes with a change in front crawl swimming speed. In addition to this, this chapter examines the inter-relationship between swimming speed, inter-arm coordination and other stroke parameters, within this specific group of impaired swimmers. Chapter 4 relates to academic aim 2, in Section 2.13.

1.6.4 Chapter 5 – Study 3

This chapter describes the coordination of the leg kick in relation to the arm stroke cycle. The chapter establishes whether the coordination of the leg kick mirrored the asymmetrical coordination of the arm stroke and examines whether leg-to-arm coordination changed at different swimming speeds. The spatio-temporal nature of leg-to-arm coordination is also discussed. Chapter 5 relates to academic aim 3, in Section 2.13.

1.6.5 Chapter 6 – Study 4

This chapter examines whether the three-dimensional, spatio-temporal nature of the upper extremity limb movements of single-arm amputee front crawl swimmers is influenced by 50 m and 400 m paced swimming. The inter-relationships between selected upper extremity kinematics are also assessed. The duration of arm stroke phases, the linear and angular displacement of the limbs and the linear velocities of the upper extremity segments are discussed. Chapter 6 relates to academic aim 4, in Section 2.13.

1.6.6 Chapter 7 – Study 5

This chapter examines how the amputees' mass centre velocity fluctuates during the underwater pull of the affected- and unaffected-arm, at 50 m and 400 m pace. The chapter discusses the link between the fluctuations in mass centre velocity and the changes in backward velocity of the arms' most distal point (i.e. stump tip and finger tip). Chapter 7 relates to academic aim 5, in Section 2.13.

1.6.7 Chapter 8 – Summary, applications, recommendations, future research

This chapter summarises the main findings of the thesis. The chapter also outlines the practical benefits of these findings to unilateral arm-amputee front crawl swimmers and to those who coach and teach them.

CHAPTER TWO

REVIEW OF RELATED LITERATURE

The aim of this chapter is to provide an extensive review of the literature on the biomechanical characteristics of front crawl swimmers. Where possible, research related to swimmers with a physical impairment will be highlighted. However, the number of published studies in this area is limited. Within the review, established biomechanical data collection techniques are also identified and discussed. This review enabled the identification of aspects of the front crawl stroke, specific to single-arm amputees, that were worthy of study. The specific topics that were researched and the academic aims of the thesis are stated at the end of this chapter.

2.1 Introduction

In general, swimming performance is determined by a swimmer's physiology (metabolic processes), morphology (stature and limb size), biomechanics (ability to generate force and transfer it the water) and psychological profile (arousal and motivation) (Toussaint & Beek, 1992). A swimmer's ability to generate force and transfer it effectively to the water is dependent upon their technique. Competitive swimmers train so that they can successfully coordinate their limb actions through a specific sequence of movements to maximise propulsion and minimise resistance.

2.2 Arm propulsion in front crawl

In able-bodied front crawl swimming, where the two arms move rhythmically in an anti-phase inter-limb relationship (Nikodelis, Kollias, & Hatzitaki, 2005), the hand and forearm segments are seen as the major propelling surfaces responsible for about 85% of the total propulsion (Toussaint & Beek, 1992). However, the exact mechanism responsible for propulsion remains unclear. Before the 1960's it was thought that, in accordance with Newton's Third Law, a swimmer moved their arm directly backward through the water thus creating a force that would propel them forward (Counsilman, 1968). It was not until the late 1960's, with the use of underwater film observations that it became apparent that swimmers did not pull their arm backward in a straight line, but instead used three-dimensional sweeps (Counsilman, 1968). These sweeps, when viewed from below, followed an S-shaped pattern. Using this pattern (Figure 2.1), it was proposed that a swimmer's hand was able to continuously find still water to push against and thus gain more resistance than it would by pushing against water that was already accelerated (Toussaint & Beek, 1992).

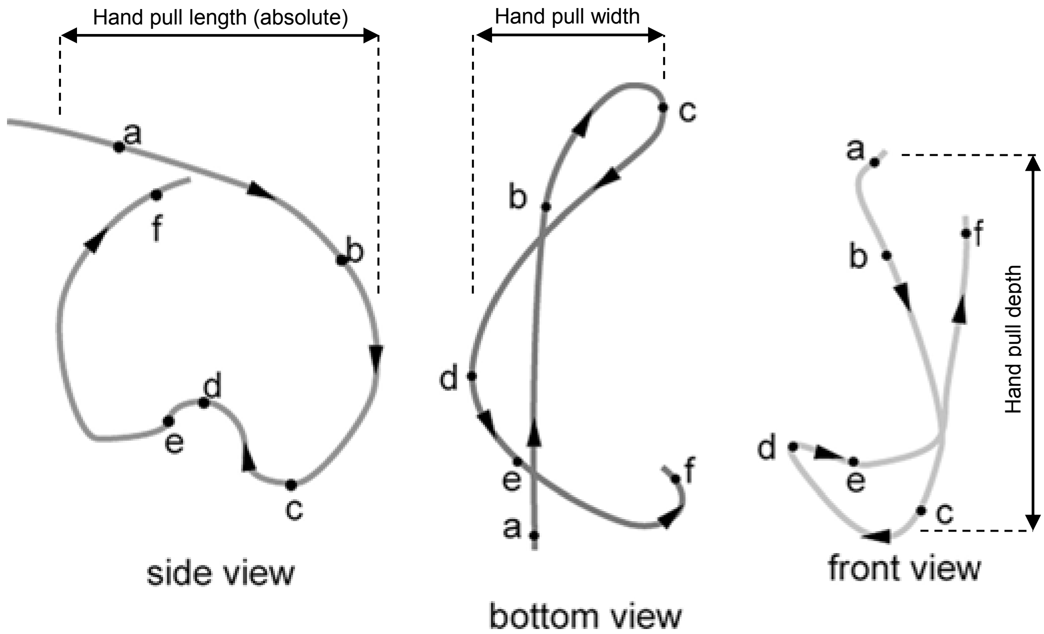


Figure 2.1. Front crawl stroke pattern (relative to the water) of the right hand in three dimensions; a-b: entry, b-c: downsweep, c-d: inward pull or insweep, d-e: outward pull, e-f: exit or upsweep. Adapted from Toussaint and Truijens (2005).

Counsilman (1971) later hypothesised that during its underwater trajectory a swimmer's hand acted like an aircraft wing and as such, utilised Bernoulli's principle to create predominantly lift as well as drag forces. Schleihauf (1979) and later Berger, de Groot and Hollander (1995), used a flow channel to determine the lift and drag coefficients for different orientations of a static replica hand at constant water speeds. Combining these data with hand velocities obtained from film recordings of swimmers, Schleihauf (1979) corroborated Counsilman's hypothesis showing that both lift and drag forces were generated during the stroke cycle and that the resultant force was directed forward (Toussaint & Truijens, 2005). Inherent in Schleihauf's method was the assumption that hydrodynamic data obtained under steady conditions (constant velocity, constant angle of attack and sweep back angle) were applicable to the conditions that exist during the actual swimming stroke, which is not the case. Given the limitations of Schleihauf's method and the large measurement errors in propulsive force calculations, derived from film recordings of swimmers (Payton & Bartlett, 1995; Sanders, 1999), an alternative approach to calculate propulsive force has recently been gaining in popularity.

Computational fluid dynamics (CFD) allows for the evaluation of the fluid flow around a swimmer's body or extremities using a computer based simulation method. Under steady flow conditions (Bixler & Riewald, 2002) and more recently under accelerated flow (Rouboa, Silva, Leal, Rocha, & Alves, 2006), CFD has shown that the drag force created by a swimmer's hand and forearm contributes more to propulsion than the lift force. These findings, together with those of Toussaint, Den Berg and Beek (2002), bring into question the application of Bernoulli's principle to accurately describe the propulsive force created by an able-bodied swimmer's "foil-shaped" hand. These studies however did not consider whether the upper-arm contributed to propulsion in front crawl (Lecrivain, Payton, Slaouti, & Kennedy, 2010). This is not surprising, given that, whilst the arm is in its propulsive phase, the most proximal end (the shoulder) moves forward relative to the water and encounters drag forces that resist its forward motion (Hay & Thayer, 1989).

To examine the propulsive contribution of the upper-arm, Lecrivain, Slaouti, Payton and Kennedy (2008) used unsteady CFD to model the partially amputated-arm of a female, below-elbow amputee swimmer. At a swimming speed of 1 $m \cdot s^{-1}$, results showed that the upper-arm contributed effectively to the propulsion of the body (Figure 2.2), with mean forces (resultant and propulsive) being equal to 7.9 and 3.2 N, respectively. Advancing this model further, Lecrivain et al. (2010) accounted for body roll and changes in arm extension velocity and mean swimming speed. In doing so, these authors found that body roll greatly enhanced the propulsive contribution of the upper-arm and that an increase in the angular velocity of the upper-arm led to a concomitant increase in the propulsive forces produced. However, as the mean swimming speed of the swimmer increased from 0.8 to 1.06 to 1.2 m·s^{-1}, the ability of the upper-arm to generate effective propulsion decreased. Thus there exists, for any given swimming speed, a minimum angular velocity at which the upper-arm must be rotated to generate effective propulsion. Further work is needed to verify whether the affected-arm of a unilateral arm amputee swimmer can contribute effectively to propulsion during high speed, full stroke front crawl swimming.

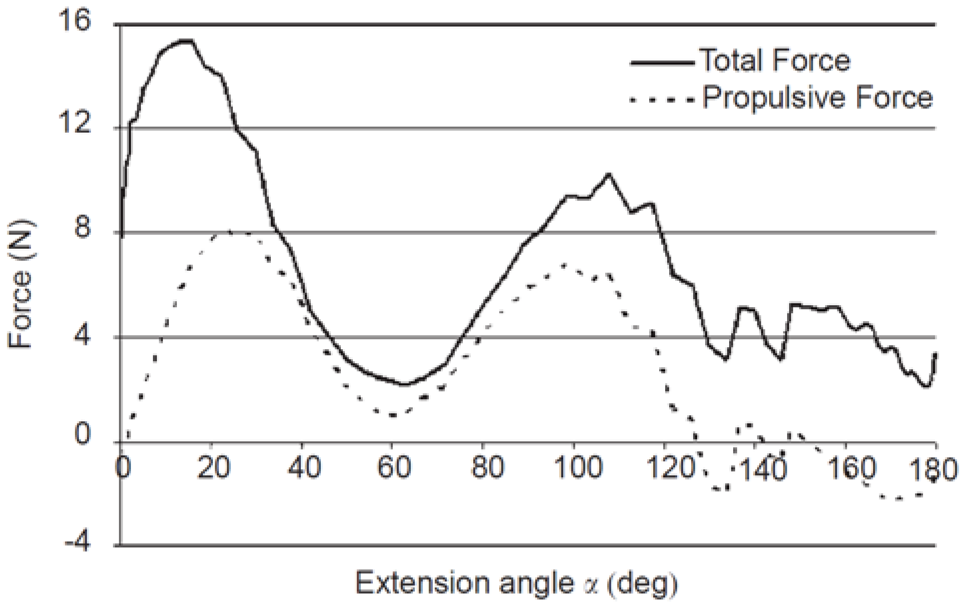


Figure 2.2. Propulsive force (against arm extension angle) generated by the upper-arm of a below-elbow amputee swimmer. Taken from Lecrivain et al. (2008).

2.3 Resistance during swimming

Resistance that acts to slow the forward progression of a swimmer is termed drag. The total drag force consists of frictional, pressure and wave drag components (Toussaint & Beek, 1992). Frictional drag is attributed to the forces tending to slow the water flowing along the surface of a swimmer's body (Sanders, Rushall, Toussaint, Stager, & Takagi, 2001). Pressure drag arises as a result of distorted water flow over a swimmer's body, the magnitude of which depends on the shape, size (cross sectional area) and velocity (squared) of a swimmer (Toussaint & Truijens, 2005). Wave drag is created when swimming near the water surface and is proportional to the velocity (cubed) of a swimmer (Sanders et al., 2001). The relative contribution of each of the three drag components depends on a swimmer's speed (Toussaint & Truijens, 2005), such that at slow speed friction drag is important, at faster speed pressure drag dominants, until at speeds greater than 1.5 $m \cdot s^{-1}$ wave drag becomes most important.

In able-bodied swimming, total drag has been measured under active and passive conditions using a variety of different devices. Hollander et al., (1986) developed the MAD system which measured active drag via fixed pads (connected to a force transducer) positioned under the water, against which swimmers pushed. Swimmers using this system however are restricted to arms only front crawl and use arm strokes that are modified, when compared to free swimming (Clarys et al., 1988). Kolmogorov and Duplishcheva (1992) developed the velocity perturbation method which estimated active drag based on attaching an object of known additional resistance to a swimmer. This method relies on the assumption that a swimmer's power output is the same between different swimming trials, which may not be the case. Using a winch, towing cable and load cell, Lyttle, Blanksby, Elliott and Lloyd (2000) measured the passive drag of able-bodied swimmers when gliding underwater in different positions and at different speeds.

Only two studies have investigated passive drag in competitive swimmers with a disability (Chatard, Lavoie, Ottoz, Randaxhe, Cazorla, & Lacour, 1992; Fulton, Pyne, & Burkett, 2011). Chatard et al. (1992) towed swimmers at a speed of 1.4 $m \cdot s^{-1}$, in a prone position with arms extended above the head. These authors determined that the degree of physical disability was related to the magnitude of the passive drag experienced by the physically impaired swimmers. Mean passive drag data from Fulton et al. (2011) for twelve Paralympic swimmers, with various physical impairments, being towed at 1.7 $m \cdot s^{-1}$, was comparable to that reported for able-bodied swimmers being towed at speeds ranging between 1.6 and 1.9 $m \cdot s^{-1}$ (Lyttle et al., 2000). Since no attempt has been made to measure the active drag of swimmers with a disability and only two studies have examined their passive drag, further work is needed to develop the current knowledge base on the effect that physical disability has on drag in swimming. This is particularly important given that swimmers with a physical impairment are often different sizes, may be missing appendages and might not have control over their limbs to create streamlined body shapes.

2.4 Anthropometric characteristics of swimmers

Body size is an important determinant of success in able-bodied front crawl swimming (Kennedy, Brown, Chengalur, & Nelson, 1990; Grimston & Hay, 1986). More successful swimmers, who tend to be taller and possess longer limbs (Pelayo, Sidney, Kheirf, Chollet, & Tourny, 1996) and a larger cross sectional area of the upper-torso (Grimston & Hay, 1986) use longer and slower strokes, when compared to smaller, less successful swimmers (Arellano, Brown, Cappaert, & Nelson, 1994). East (1970) speculated that taller swimmers might be able to apply higher propulsive forces, than shorter swimmers, during each stroke cycle and might do so for a longer time period due to a longer hand path trajectory. Grimston and Hay (1986) suggested that swimmers with broad shoulders are likely to have large muscles in the upper-region of the torso responsible for shoulder extension. With long arms and large hands a swimmer might be able to transfer the force generated by these muscles more effectively to the water, when compared to a swimmer with shorter and smaller limbs. As the size of the propelling surface is directly related to propelling efficiency (Toussaint, 1990), tall, broad and long-limbed swimmers might use a higher proportion of their power output to overcome drag while at the same time expend less power in moving water backward, when compared to physically smaller swimmers.

Studies involving physically impaired swimmers generally recruit participants that are younger, shorter and lighter than studies with able-bodied swimmers (Table 2.1). Although when comparing relatively recent studies, swimmers with a disability appear to be of a similar body height (Payton & Wilcox, 2006 vs. Wells, Schneiderman-Walker, & Plyley, 2006) and body mass (Fulton, Pyne, & Burkett, 2009 vs. Pelayo et al., 1996) to able-bodied swimmers of approximately the same chronological age. Given these similarities, the relationships that exist between body size and swimming performance for able-bodied swimmers, might also exist for swimmers with a disability. To date, there has been no examination of the anthropometric characteristics of highly trained swimmers with a disability. Further work is needed to establish which anthropometric characteristics are important determinants of success within and between groups of swimmers with a specific physical impairment and how these characteristics relate to stroke parameters.

Table 2.1. Selected studies that report physical characteristics of front crawl swimmers.

Study	Swimmers	Gender	Number of participants	Performance level	Age (years)	Height (m)	Mass (kg)
Grimston & Hay (1986)	Able-Bodied	Male	12	Collegiate	N/K	1.85	78.4
Chengalur & Brown (1992)	Able-Bodied	Male	57	Olympians (1988)	20.6	1.86	N/K
	Able-Bodied	Female	38	Olympians (1988)	19.4	1.72	N/K
Pelayo et al. (1996)	Able-Bodied	Male	88	Elite & International	21.7	1.84	76.3
	Able-Bodied	Female	85	Elite & International	19.1	1.72	59.7
Lyttle et al. (2000)	Able-Bodied	Male	16	National	19.3	1.81	77.8
Wells et al. (2006)	Able-Bodied	Male	89	International & National	16	1.78	67.5
	Able-Bodied	Female	106	International & National	15	1.67	58.6
Hellard et al. (2007).	Able-Bodied	Female	16	Olympians (2004)	23	1.73	N/K
	Able-Bodied	Female	16	International & National	20	1.71	N/K
Chatard et al. (1992)	Disabled	Male	21	Elite & International	19.4	1.63	55.1
	Disabled	Female	13	Elite & International	17.7	1.56	45.7
Fulton et al. (2009)	Disabled	Male	8	Paralympians	20.9	1.79	74.4
	Disabled	Female	6	Paralympians	18.0	1.54	55.2
Payton & Wilcox (2006)	Unilateral Arm Amputees	2 Male & 6 Female	8	Highly-Trained	17.6	1.69	60.6

N/K – not known

2.5 Front crawl stroke parameters

Front crawl swimming is a form of cyclical locomotion (Hay, 2002), the speed of which is the product of stroke length (m) and stroke frequency (Hz). For a given swimming speed, any change in stroke frequency will bring about an inverse change in stroke length (Craig & Pendergast, 1979). Several investigators have examined the relationships between swimming speed, stroke frequency and stroke length for competitive able-bodied front crawl swimmers. With an increase in stroke frequency, swimming speed has been reported to increase to a maximum (Figure 2.3), beyond which any further increases in stroke frequency result in a reduction in speed (Craig & Pendergast, 1979; Hay, 2002). These changes coincide with a decrease in stroke length (Keskinen & Komi, 1993; Seifert, Chollet, & Bardy, 2004).

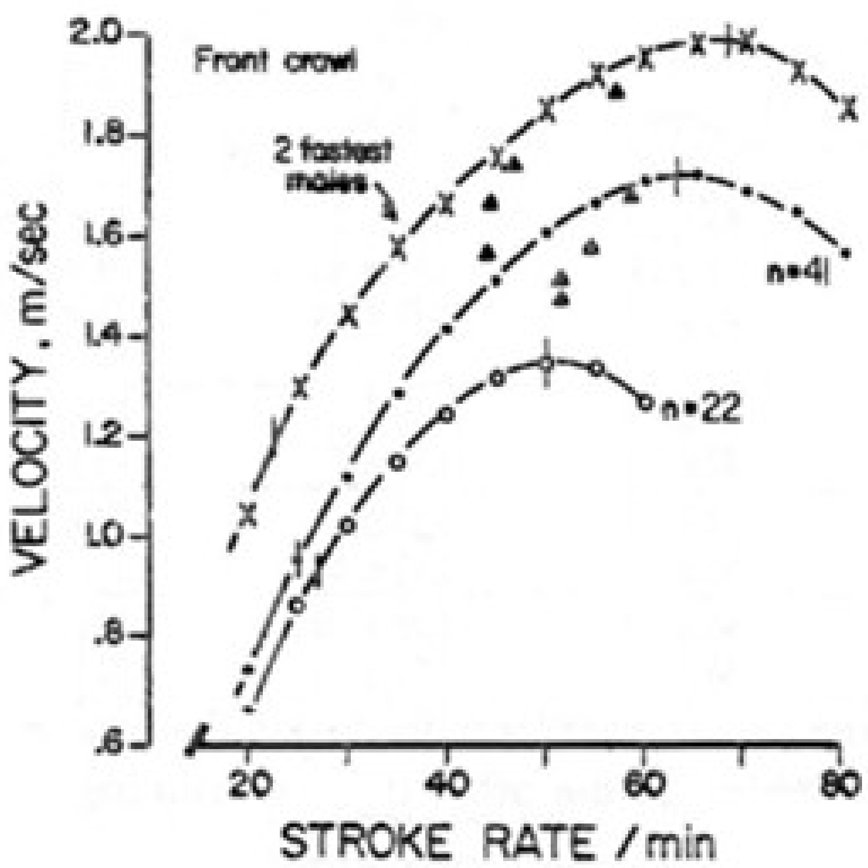


Figure 2.3. Relationship of front crawl swimming velocity to stroke rate (frequency). Taken from Craig and Pendergast (1979).

Expert swimmers are able to use longer and slower strokes to swim at slow speeds, when compared to "less skilled" swimmers (Craig & Pendergast, 1979) and are able to maintain these longer strokes as stroke frequency increases, resulting in higher front crawl swimming speeds. In competition, more successful swimmers use longer strokes (Arellano et al., 1994; East, 1970) than their less successful counterparts. Males achieve higher speeds than females using longer stroke lengths, not higher stroke frequencies (Arellano et al., 1994; Kennedy et al., 1990; East, 1970; Pelayo et al., 1996). Thus in able-bodied front crawl, stroke length is recognised as being important for successful performance.

More recently, the stroke parameters of competitive front crawl swimmers with a disability have been examined. Daly, Djobova, Malone, Vanlandewijck and Steadward (2003) and Pelayo, Sidney, Moretto, Wille and Chollet (1999) concluded that swimmers across a range of disability groups showed certain similarities with able-bodied swimmers. From their competition analysis of 72 males and 62 females, in the 100 m freestyle finals (IPC Class S2 – S10) at the 2000 Paralympic Games, Daly et al. (2003) found that within-race speed changes were primarily related to changes in stroke frequency as were speed changes between heats and finals. Swimming speed and stroke length were also found to increase as the severity of a swimmer's disability decreased. This latter finding supported the earlier work of Pelayo et al. (1999). These authors analysed the stroke parameters of 62 males and 57 females in the 100 m freestyle finals (IPC Class S3 – S10) at the 1995 European Championships and found that swimming speed and stroke length significantly increased according to the level of ability, from IPC S3 to S10 Class.

Like most studies involving swimmers with a disability, Daly et al. (2003) and Pelayo et al. (1999) grouped swimmers according to the international "Functional Classification System" under which persons with diverse impairments compete in the same class. For example, in the current IPC S9 Class for front crawl, a unilateral arm amputee might compete against a double leg below-knee amputee and a walking paraplegic in the same race. Therefore, the information presented by Daly et al. (2003) and Pelayo et al. (1999) might not be applicable to all swimmers within a class as it was not impairment specific. It is highly likely that as a result of their particular impairment, swimmers within a class might use different combinations of stroke length and stroke frequency to attain a given speed. Consequently, future research needs to target specific groups of swimmers who have the same unique disability, rather than functional groups containing swimmers with diverse physical impairments.

Only Burkett and Mellifont (2008) have presented stroke parameter data, from a competition environment, for a swimmer with a unique physical impairment. These authors tracked the performance of an IPC S9 Class swimmer (a single, elbow-level amputee) from his inaugural international competition in 2002 at the age of 14, through to his Paralympic and World record swims four years later. The 11% improvement in 100 m front crawl time over the four year period corresponded to an 11% increase in mean swimming speed and a 9% increase in stroke length, while stroke frequency decreased by 1%. Such performance gains are higher than the expected 1–2% annual improvement reported by Fulton, Pyne, Hopkins and Burkett (2009). However, it is unclear whether the swimmer's improvement was as a direct consequence of his growth and maturation, his swimming ability, his coaching and sport science support programme or a combination of factors. Further work is required to examine the relationships between stroke parameters at different swimming speeds for homogenous groups of highly-trained swimmers with the same unique impairment, such as those with a single-arm amputation.

2.6 Front crawl arm technique

When describing the front crawl arm stroke technique, it is typically broken down into a series of propulsive and non-propulsive phases (e.g., Figures 1.3 & 2.1), the number of which depends on the different phase definitions and methods of analysis. When using two-dimensional videography, the position of the hand or finger-tip is normally used to define the following phases: (1) Entry and Catch; (2) Pull; (3) Push; and (4) Recovery (Chollet, Chalies, & Chatard, 2000; Seifert et al., 2004; Seifert, Chollet, & Rouard, 2007). These phases correspond approximately to those described using three-dimensional analysis techniques (Maglischo et al., 1988, Payton & Lauder, 1995, Schleihauf et al., 1988), as follows: (1) the two-dimensional Entry and Catch correspond to the three-dimensional equivalents of Entry, Glide and part of the Downsweep; (2) Pull corresponds to part of the Downsweep and the Insweep; (3) Push corresponds to the Outsweep and Upsweep; and (4) Recovery using both methods of analysis is similarly defined. Due to the ambiguity between the methods of analysis and the variety of phase definitions used by different authors, it is often difficult to make accurate inter-study comparisons. This difficulty is likely to be compounded when studying swimmers with a physical impairment, such as those missing a finger-tip, hand or forearm segment. Hence, it may be necessary to adapt the current phase definitions for able-bodied swimmers, to more appropriate definitions for swimmers who compensate for existing anatomical deficiencies by using unique, modified variations in their arm stroke technique (Prins & Murata, 2008).

The manner in which a swimmer moves their hand through the water depends on the motion at the swimmer's joints. Mathematical models (Hay, Liu, & Andrews, 1993; Payton, Hay, & Mullineaux, 1997) demonstrated that medial hand motion during the Insweep could be achieved entirely by body roll (rotation of the body about its long axis). These models however did not accurately represent the movements of the body or upper extremity during actual front crawl swimming. Payton et al. (1999) showed that body roll opposed, rather than assisted, medial hand motion during the Insweep (Figure 2.4), as the body rolled back to toward the neutral position (Payton et al., 2002) during this phase.

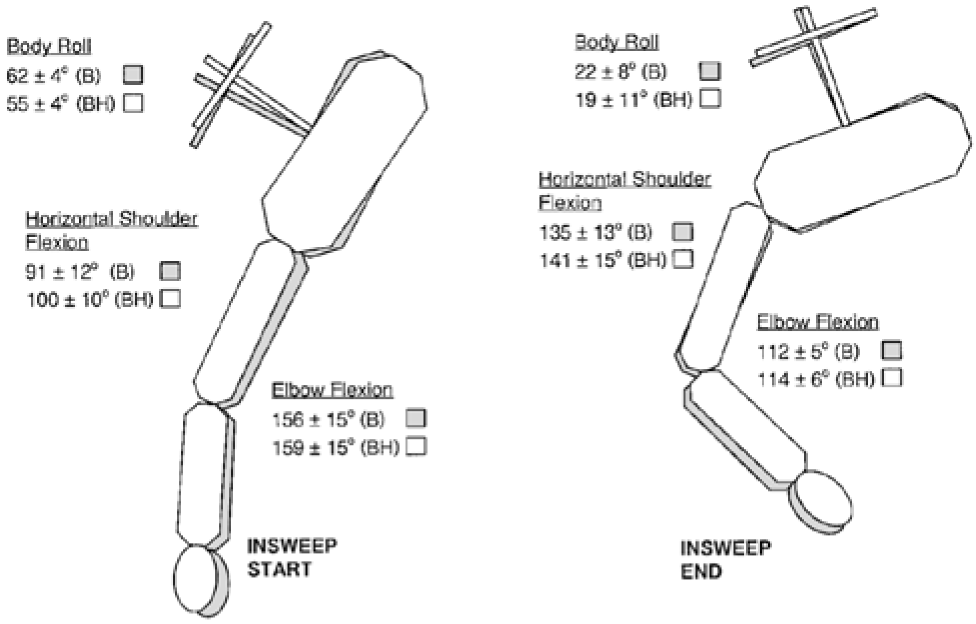


Figure 2.4. Front view of the trunk and upper extremity position at the start and end of the Insweep phase, for breathing (B) and breath-holding (BH) trials. Taken from Payton et al. (1999).

In able-bodied front crawl swimming, the velocity of the hand and forearm segments relative to the water is important for successfully generating propulsion (Payton et al., 2002). During the underwater pull, the Insweep and Upsweep are phases where swimmers can generate the highest hand velocities (Payton & Lauder, 1995) and consequently the highest propulsive forces (Maglischo et al., 1988, Schleihauf et al., 1988). For thirteen male national level front crawl swimmers, Payton & Lauder (1995) reported peak inward and backward hand velocities of 2.09 ± 0.39 $m \cdot s^{-1}$ and 1.50 ± 0.47 $m \cdot s^{-1}$, respectively, during the Insweep. Such velocities are produced primarily from shoulder extension, with lesser contributions from horizontal shoulder flexion, internal rotation of the shoulder and elbow flexion (Payton et al., 2002). During the Upsweep, where swimmers generate the highest propulsive forces (Maglischo et al., 1988, Schleihauf et al., 1988), peak outward and backward hand velocities of 1.90 ± 0.65 $m \cdot s^{-1}$ and 1.88 ± 0.26 $m \cdot s^{-1}$, respectively, have been reported (Payton & Lauder, 1995). It is likely that shoulder flexion, horizontal shoulder extension and external rotation of the shoulder, elbow extension and body roll combine to produce high hand velocities during a swimmer's final backward, upward and outward push of their underwater stroke (Payton et al., 2002).

The displacement of a swimmer's hand during the stroke cycle depends on body roll, shoulder and elbow flexion/extension and the length of the swimmer's arm. The maximum depth that a swimmer's hand reaches (Figure 2.1), below the water surface, ranges between 0.66 ± 0.05 m and 0.77 ± 0.03 m (McCabe, Psycharakis, & Sanders, 2011; Payton & Lauder, 1995; Perrier & Monteil, 2004; Scheihauf et al., 1988). These values are substantially greater than those (0.40 to 0.50 m) reported by Cappaert, Pease and Troup (1995) for twelve Olympic male 100 m front crawl swimmers who had a mean height of 1.88 m. Cappaert (1999) later reported pull depths ranging between 1.0 and 1.6 m for male distance (n = 4) and sprint (n = 5) front crawl swimmers, respectively, who had competed at the 1992 and 1996 Olympic Games. Given that the values reported by Cappaert et al. (1995) and Cappaert (1999) are very different compared to other front crawl studies, their findings should be treated with caution. Underwater hand pull widths (Figure 2.1) have been reported to range between 0.27 ± 0.09 m and 0.39 ± 0.07 m (McCabe et al., 2011; Payton & Lauder, 1995; Perrier & Monteil, 2004; Scheihauf et al., 1988). Scheihauf et al. (1988) and Payton and Lauder (1995) reported values of 0.65 ± 0.10 m and 0.60 ± 0.06 m, respectively, for the distance that the hand travelled backward relative to the water (i.e. slippage) during the underwater stroke (Figure 2.1). Currently, it is unclear whether the hand on the unaffected-arm of a unilateral arm amputee follows a similar three-dimensional trajectory to that of an able-bodied swimmer. In order to compensate for their missing limb, single-arm amputees might modify the motion of their unaffected-arm rather than use a similar stroke pattern to that used by able-bodied swimmers.

Only two studies have discussed the upper-limb kinematics of front crawl swimmers with a physical impairment. In the first, Prins and Murata (2008) presented a kinematic analysis of swimmers with a physical disability, including one female unilateral arm amputee (site of impairment unknown). Although the amputee was likely to be a recreational swimmer (she swam at 0.35 $m \cdot s^{-1}$, which is exceptionally slow [4 min 54 s for 100 m], with a stroke length of 0.5 m), these authors identified a key feature of her arm stroke technique. At the point when the affected-arm entered the water it distinctly paused, whereas the unaffected-arm did not. These authors reasoned that this delay (25% of total stroke time) maintained the stable rhythm of the swimmer's overall arm stroke cycle. Further work is needed to examine whether this asymmetrical inter-arm coordination is purely a feature of one recreational swimmer or whether it is a common feature for all unilateral arm amputees, including competitive swimmers, over a range of swimming speeds.

The second study examined the intra-cyclic velocity fluctuations of eight (2 male and 6 female) highly-trained unilateral arm amputees during arms-only front crawl (Payton &Wilcox, 2006). Although swimmers where observed to exhibit a variety of different timings between their two arm strokes, these authors did not examine which timings were more conducive to swimming performance. Furthermore, it was reported that the extension velocity of the swimmers' affected-arm did not correlate with the peak swimming speed during the underwater pull of the same limb. Consequently, these authors speculated that, rather than limb speed, factors such as the timing and trajectory of the pull may be more important in determining the effectiveness of the pull. Further work is needed to accurately describe the three-dimensional arm kinematics of unilateral arm amputee front crawl swimmers and to examine how upper extremity limb kinematics relate to swimming performance.

2.7 Body roll in front crawl

In able-bodied front crawl, the rotation of a swimmer's torso about its long axis, or body roll, is an essential feature of the stroke. Body roll may serve several functions including: facilitating the breathing action and aiding arm recovery (Maglischo, 2003), generating hand speed and consequently propulsion (Payton et al., 2002) and reducing form drag (Kolmogorov & Duplischcheva, 1992). In able-bodied front crawl, the dominant mechanism for generating body roll is buoyant force (Yanai, 2004), although external fluid forces in non-propulsive directions (Yanai, 2003) and internal reaction forces from limb accelerations (Payton et al., 1999) also contribute.

A wide range of maximum body roll angles have been reported in the literature, which can be partly attributed to the different definitions of body roll and their corresponding methods of calculation. Using two-dimensional videography, analysis of the motion of a dorsal fin attached to a swimmer's torso resulted in maximum body roll angles of 57 ± 4° and 66 ± 5° for skilled able-bodied male front crawl swimmers during breathing and non-breathing trials, respectively (Payton et al., 1999: n = 6). Using three-dimensional analysis techniques, maximum shoulder roll angles have been reported to be: 34 ± 2° and 35 ± 3° for elite and sub-elite male swimmers, respectively (Cappaert et al., 1995: n = 10); 75° and 66° for collegiate males swimming at moderate and sub-maximal pace, respectively (Yanai, 2003: n = 11) and 50 ± 5° and 57 ± 5° for the dominant and non-dominant side of international male swimmers, respectively (Psycharakis & Sanders, 2008: n = 10).

Given that the torque exerted by the buoyant force about a swimmer's long axis, as the arm is recovered over the water, is the primary mechanism for driving body roll in able-bodied front crawl (Yanai, 2004), a swimmer with a physically impaired arm, such as a single-arm amputee, might have a limited ability to generate body roll. Thus, considerable asymmetry might be expected in the body roll of unilateral arm amputee front crawl swimmers. This has important implications for these swimmers and for those who coach them. For example, without sufficient body roll, the act of breathing becomes difficult to execute without it interfering with a swimmer's ability to produce propulsion, or with it increasing the amount of resistance experienced by their body.

2.8 Front crawl leg kick

In front crawl, the leg kick may serve several functions including: stabilising body roll (Counsilman, 1968; Yanai, 2003), streamlining the body (Counsilman, 1971) generating propulsion (Bucher, 1975; Hollander, de Groot, van Ingen Schenau, Kahman, & Toussaint, 1988; Sanders & Psycharakis, 2009) and enhancing the effectiveness of the arm pull (Deschodt, Arsac, & Rouard, 1999; Watkins & Gordon, 1983). There is agreement that maximal swimming speed during full stroke front crawl is reduced by approximately 10% when swimming arms only (Bucher, 1975; Deschodt et al., 1999; Watkins & Gordon, 1983). It is probable that the leg kick ensures ongoing propulsion, during the phases when the arm stroke is non-propulsive. This would enable a swimmer to travel further down the pool with each arm stroke, when compared to swimming arms only (Deschodt et al., 1999).

For front crawl swimmers with various physical impairments, the amplitude, rate and number of leg kicks have been examined (Fulton et al., 2009; 2011). Findings from these studies suggest that: (1) a disabled swimmer's preferred, self selected, leg kick amplitude corresponds closely to an optimal. A swimmer's preferred kick allows for the attainment of optimal swimming speed without increasing drag; and (2) disabled swimmers adopt a consistent kick beat pattern when swimming and when kicking only, during a 100 m time trial. However, as Fulton et al. (2011) did not relate the swimmers' kick rate and kick count to the swimmers' arm stroke cycle during the 100 m swimming trial, it is not possible to say what the most common kicking action was for these physically impaired swimmers.

Front crawl leg kick consists of a number of upbeats and downbeats of each leg per arm stroke cycle. The most commonly reported kicking action in able-bodied front crawl swimming is often referred to as a six-beat kick (Sanders & Psycharakis, 2009; Yanai, 2003), although swimmers also use four-beat and two-beat kicks when swimming front crawl at different speeds (Chollet et al., 2000; Millet, Chollet, Chalies, & Chatard, 2002). The choice of leg kick used by a swimmer is likely to be dependent on his or her physical characteristics, the event distance being swum and the swimmer's preferred leg-to-arm coordination learnt during training (Persyn, Daly, Vervaecke, Van Tilborgh, & Verhetsel, 1983).

In able-bodied front crawl, the leg kicks are rhythmically executed within the arm stroke cycle, such that the downbeats of the kick clearly coincide with particular phases of the arm stroke (Eaves, 1971; Maglischo, 2003; Persyn et al., 1983; Yanai, 2003). With a six-beat kick, the first downbeat of the left leg coincides with the Entry and Glide phase of the right arm, the following downbeat of the right leg is executed during the Downsweep phase of the right arm and the second downbeat of the left leg occurs as the right arm completes the Insweep phase (Maglischo, 2003; Yani, 2003). This is then repeated on the other side of the body. Such leg-to-arm coordination suggests that able-bodied front crawl swimmers align their leg kick with their arm stroke to enhance performance, rather than kicking their legs independently of moving their arms. A swimmer's ability to integrate the timing of their leg kick effectively into the arm stroke cycle is important for fast swimming, more so than being able to attain a high speed when just kicking. Given the clear leg-to-arm coordination in able-bodied front crawl, and the various inter-arm timings exhibited by unilateral arm amputees (Payton & Wilcox, 2006), further work is needed to examine how this latter group of swimmers coordinate their leg kick with their asymmetrical arm stroke.

2.9 Inter-arm coordination in front crawl

When evaluating the effectiveness of a swimmer's stroking technique an understanding of the interplay between propulsion and resistance is crucial. Using members of the 1984 U.S. Olympic Swimming Team, Maglischo et al. (1988) demonstrated that while there were four propulsive phases in the front crawl underwater arm stroke action: (1) Downsweep; (2) Insweep; (3) Outsweep; and (4) Upsweep, swimmers were unable to generate large propulsive forces in more than two of these phases. Later, Chatard, Collomp, Maglischo and Maglischo (1990) reported that "skilled" front crawl swimmers were characterised by their ability to overlap the propulsive Downsweep phase of one arm with the propulsive Upsweep phase of the other, which they termed superposition. This allowed these "skilled" swimmers to attain higher swimming speeds with higher stroke frequencies, when compared to "less-skilled" swimmers.

Based on these studies, Chollet, et al. (2000) formulated a new Index of Coordination (IdC) for the front crawl (Figure 2.5). The IdC separates the complete cycle of each arm into four distinct phases: (A) Entry and Catch; (B) Pull; (C) Push; (D) Recovery, of which two are propulsive (B and C) and two are non-propulsive (A and D). The IdC quantifies the coordination of arm movements in front crawl by measuring the time lag between the beginning of propulsion from one arm stroke and the end of propulsion from the other. Arm coordination conforms to one of three major models: (1)

Catch-up describes a time delay between the propulsive phases of the two arms (IdC < 0%); (2) *Opposition* describes a continuous series of propulsive actions: one arm begins the Pull phase when the other is finishing the Push phase (IdC = 0%); (3) The *Superposition* model, as mentioned previously, describes an overlap, to a greater or lesser extent, of the propulsive phases (IdC > 0%).

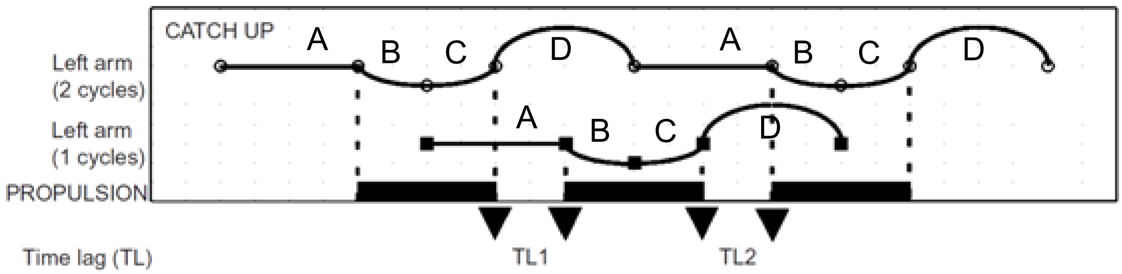


Figure 2.5. Catch-up coordination, described using the IdC. Adapted from Seifert et al. (2004).

Many studies have used the IdC to examine the arm coordination of competitive able-bodied front crawl swimmers under various conditions. There is agreement that able-bodied swimmers modify their arm coordination with increases in swimming speed (Chollet et al., 2000; Potdevin, Bril, Sidney, & Pelayo, 2006; Seifert et al., 2004). Such changes coincide with an increase in stroke frequency. Arm coordination has been shown to vary between different performance levels (Chollet et al., 2000; Millet et al., 2002; Seifert et al, 2007). The fastest front crawl swimmers are generally characterised by higher IdC values (opposition and superposition) when compared to their slower counterparts, who tend more towards catch-up. Higher IdC values have been shown to correlate significantly with higher stroke frequencies (Chollet et al., 2000: r = .67; Seifert et al., 2004: r = .76). Differences in arm coordination between genders have also been reported (Seifert, Boulesteix, & Chollet, 2004; Seifert, Chollet, & Allard, 2005). Males who are taller, faster and use longer strokes than females achieve higher speeds and tend to exhibit more superposition. Females tend more towards opposition or catch-up. Furthermore, male swimmers suddenly switch from using catch-up at slow swimming speeds to opposition or superposition at a critical speed of 1.8 m·s^{-1} (Figure 2.6), whereas female swimmers adapt their coordination progressively (Seifert, Boulesteix, & Chollet, 2004).

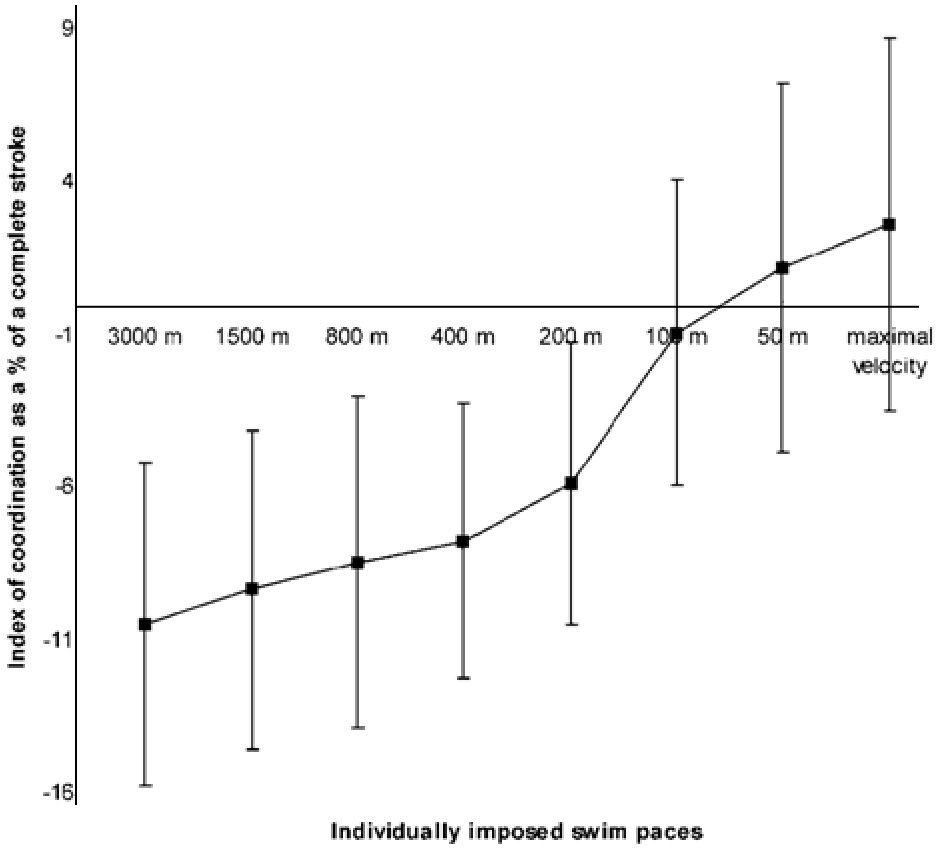


Figure 2.6. Mean (± SD) index of coordination for individually imposed swim paces. Taken from Seifert et al. (2004).

The arm coordination patterns used by competitive front crawl swimmers with a disability have received very little attention in the research literature. Presently, only Satkunskiene, Schega, Knuze, Birzinyte and Daly (2005) appear to have addressed this specific research area. The stroking technique of eighteen well-trained swimmers with diverse loco-motor disabilities (IPC Class S3 – S10) was evaluated, at mean mid-pool

100 m race speed, using the IdC. These authors concluded that "more-skilled" swimmers were characterised by greater amounts of superposition and higher stroke frequencies, when compared to "less-skilled" swimmers. However, due to the diverse functional impairments of the swimmers across the functional classes, large variations existed between the disabled swimmers' stroking techniques. Consequently, this research provides little information about the effect of a specific physical impairment on swimming technique and performance. Further work is needed to examine the arm coordination strategies of swimmers who have a specific type of physical impairment, such as front crawl swimmers with a single-arm amputation.

2.10 Intra-cyclic velocity fluctuations

When swimming, the movements of a swimmer's arms and legs lead to velocity fluctuations of the swimmer's mass centre in the direction of travel. Increased velocity fluctuations within a stroke cycle are related to an increased energy cost (Barbosa, Keskinen, Fernandes, Colaço, Lima, & Vilas-Boas, 2005; Nigg, 1983). As competitive swimmers train to successfully coordinate their limb actions through a specific sequence of movements, it would be expected that elite swimmers might have lower intracylic velocity fluctuations than sub-elite swimmers. Schnitzler, Seifert, Alberty and Chollet (2010) reported that elite front crawl swimmers, who had a lower IdC compared to recreational swimmers, also had lower intra-cyclic velocity fluctuations. Cappaert et al. (1995) suggested that elite front crawl swimmers minimised the reduction in their swimming velocity, during phases in the stroke cycle where propulsion was less than resistance, by using better streamlined body positions than sub-elite swimmers. For the other competitive strokes however, the effect of skill-level on intra-cyclic velocity fluctuations is less clear (Psycharakis, Namei, Connaboy, McCabe, & Sanders, 2010).

All four competitive strokes are characterised by significant velocity fluctuations within each stroke cycle. In butterfly, horizontal velocity fluctuations may be as much as ± 50% from the mean swimming speed (Barbosa et al., 2005; Mason, Tong, & Richards, 1992; Sanders, 1996[a]), in breaststroke ± 45% (Colman, Persyn, Daly, & Stijnen, 1998; D'Acquisto & Costill, 1998; Sanders 1996[b]) and in back stroke ± 15% (Craig & Pendergast, 1979). In able-bodied front crawl, intra-cyclic velocity fluctuations have been reported to range between ± 14% and ± 23% (Alberty, Sidney, Huot-Marchand, Hespel, & Pelayo, 2005: ± 23%; Craig & Pendergast, 1979: ± 20%; Psycharakis et al., 2010: ± 22%; Schnitzler et al., 2010: ± 14% and ± 18%). For swimmers with a single-arm amputation, intra-cyclic velocity fluctuation during arms-only front crawl (Figure 2.7) was reported to be ± 18% from the mean swimming speed (Payton & Wilcox, 2006).

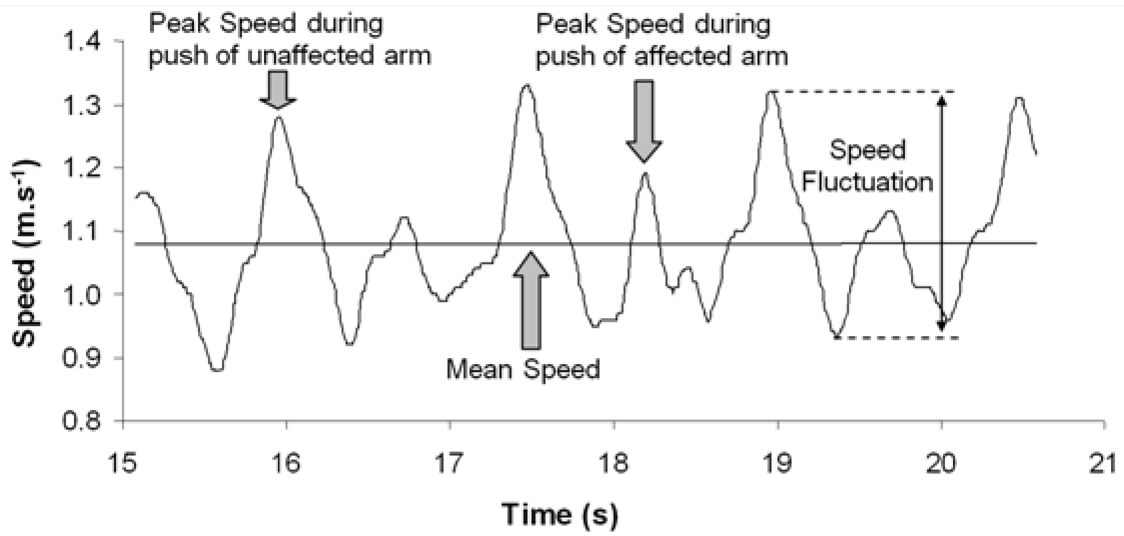


Figure 2.7. Intra-cyclic speed-time curve for three consecutive stroke cycles of an arm amputee front crawl swimmer. Taken from Payton and Wilcox (2006).

Researchers have used different approaches to calculate intra-cyclic velocity fluctuations in swimming. The most common method is to express the difference between the maximum and minimum instantaneous velocity, attained during the stroke cycle, as a percentage of a swimmer's mean velocity (Craig & Pendergast 1979; Payton & Wilcox, 2006; Psycharakis et al. 2010). Another approach is to separately express the maximum and minimum instantaneous velocity as a percentage of mean swimming velocity (Alberty et al., 2005). The third approach is to calculate intra-cyclic velocity fluctuations by determining the coefficient of variation of the swimmer's velocity during a stroke cycle (Schnitzler et al., 2010). This latter approach could, in part, explain the lower intra-cyclic velocity fluctuations reported by Schnitzler et al. (2010) compared to other front crawl studies.

Instantaneous swimming velocity has often been measured using two-dimensional videography (Barbosa et al., 2005; Colman et al., 1998; Mason et al., 1992; Sanders, 1996[a, b]) or purpose-built devices (Alberty et al., 2005; Craig & Pendergast, 1979; D'Acquisto & Costill, 1998; Payton & Wilcox, 2006; Schnitzler et al., 2010) attached to a fixed point on a swimmer's body via a wire. These methods, while being user-friendly and time and cost efficient, have limitations. First, using a purpose-built device attached to a fixed point such as the hip does not represent accurately the kinematics of a swimmer's mass centre (Barbosa et al., 2005; Mason, et al., 1992; Psycharakis & Sanders, 2009). Second, vertical movements of a fixed point might be misinterpreted by purpose-built wire devices as forward displacements (Craig & Pendergast, 1979). Third, when using two-dimensional videography to determine mass centre velocity (e.g., Barbosa et al., 2005; Colman et al., 1998; Mason et al., 1992; Sanders, 1996[a, b]) bilateral symmetry must be assumed. This is often not the case. Swimmers typically show asymmetries in their stroke technique (Arellano, Lopez-Contreras, & Sanchez-Molina, 2003; Seifert et al., 2005). Fourth, since swimming is a three-dimensional movement, two-dimensional videography cannot account for all the rotations of the body and limbs. Thus, three-dimensional analysis techniques, although often limited to the study of a single stroke cycle, must be used to accurately determine the exact motion of a swimmer's limbs and the resultant velocity fluctuations of their centre of mass.

2.11 Whole body three-dimensional analysis techniques

Due to the time involved (manual digitising of body landmarks for one stroke cycle), cost of resources (multiple synchronised cameras), associated errors (image distortion; digitising errors due to water disturbances and bubbles; large performance volumes) and complexity of analysis (motion of limbs through air and water; individualising body segment parameter data), few studies have determined whole body mass centre motion using three-dimensional analysis techniques, during swimming.

Cappaert et al. (1995) conducted a comparison between six elite and six sub-elite 100 m front crawl swimmers at the 1992 Olympic Games. Two below and two above water cameras were used to record the swimmers' performance through a previously calibrated volume (2.0 × 1.4 × 2.0 m for the forward, lateral and vertical directions, respectively). For each camera view, twenty-four landmarks on each swimmer's body were digitised for a stroke cycle. Image coordinates were reconstructed using a Direct Linear Transformation (DLT) algorithm (Abdel-Aziz & Karara, 1971) to three-dimensional object-space coordinates, which were used to define a 14-segment body model. However, no reconstruction errors were specified by the authors. Given the rather small calibration frame used, relative to the height of the swimmers (1.88 m), it is likely that rather large reconstruction errors occurred. These errors might account for the different kinematic values reported by Cappaert et al. (1995) compared to other front crawl studies (e.g., McCabe et al., 2011; Payton & Lauder, 1995; Scheihauf et al., 1988).

Studying the wave characteristics of eight male and eight female butterfly swimmers at the 1991 World Championships, Sanders, Cappaert and Devlin (1995) also used four fixed camera views and a 14-segement model (Dempster, 1955) to determine each swimmer's mass centre displacement. Although the size of the calibrated performance volume was not reported, average root mean square errors of the reconstructed (Abdel-Aziz & Karara, 1971) calibration coordinates were 6 mm, 3 mm and 2 mm for the forward, vertical and lateral directions, respectively.

To determine the angular momentum of a swimmer's entire body about its long axis, Yanai (2001; 2003) combined the use of two panning periscopes (Yanai, Hay, & Gerot, 1996), each of which could simultaneously view a swimmer's above and underwater motions, with panning DLT procedures (Yu, Koh, & Hay, 1993). From these camera views, twenty-one landmarks were digitised to define a 14-segment model. Cadaver data (Clauser, McConville, & Young, 1969) were used in both studies to determine the masses and centre of mass locations of individual limb segments. Mean absolute reconstruction errors were 8 mm for the above water and 9 mm for the below water volumes (Yanai, 2001) or less than 3% of the performance volume dimensions (8.4 × 1.5 × 2.0 m for the forward, lateral and vertical directions, respectively) (Yanai, 2003).

More recently, at the Centre for Aquatics Research and Education (University of Edinburgh) intra-cyclic velocity fluctuations (Psycharakis et al., 2010) and limb kinematics (McCabe et al., 2011) have been determined for able-bodied front crawl swimmers, within and between different race pace swims. In their studies, both Psycharakis et al. (2010) and McCabe et al. (2011) used six stationary and synchronised cameras (four below and two above water cameras) to record swimmers' performances through a previously calibrated 6.75 m^3 volume (Figure 2.8). Both authors referred to Psycharakis, Sanders and Mill (2005) when determining the accuracy and reliability of their DLT (Abdel-Aziz & Karara, 1971) calculations. Average (± SD) root mean square errors were 3.9 ± 0.4 mm, 4.8 ± 0.4 mm and 3.8 ± 0.05 mm for the forward (*X*), lateral (*Y*) and vertical (*Z*) directions, respectively (Psycharakis et al., 2005). When expressed relative to the dimensions of the performance volume, the corresponding percentage errors were 0.1%, 0.5% and 0.2%. These reconstruction errors are comparable to those reported by Payton et al. (1999; 2002). In their studies, mean absolute reconstruction errors were 3.1 mm, 2.0 mm and 1.5 mm in the forward, lateral and vertical directions, respectively. The corresponding percentage errors were 0.24%, 0.23% and 0.16% of the dimensions of the calibration frame (1.30 × 0.93 × 0.88 m).

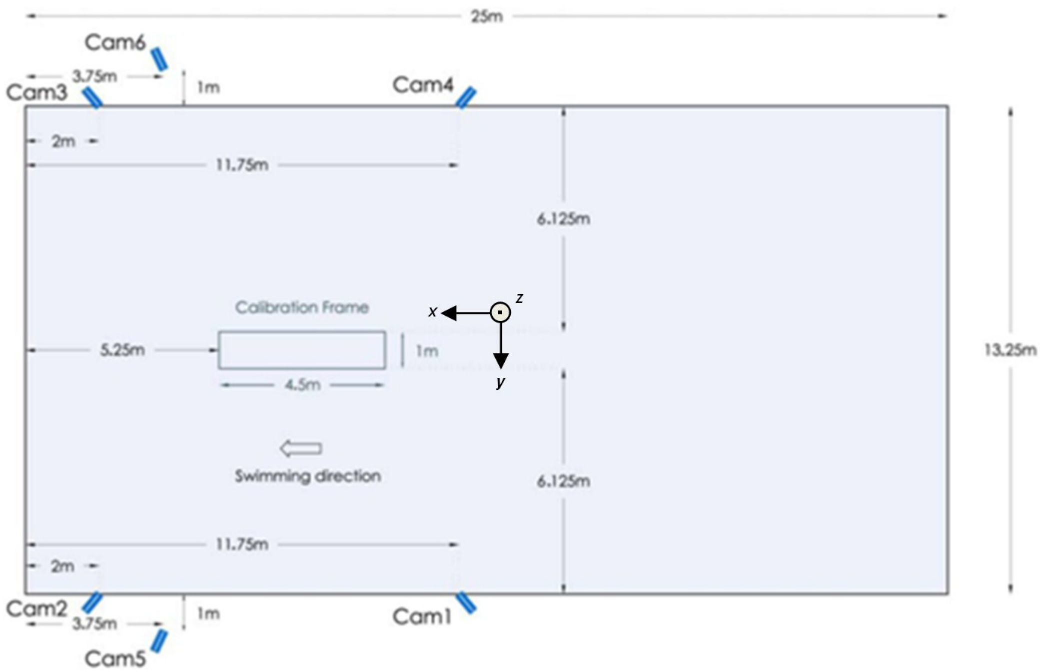


Figure 2.8. Positions of cameras and calibration space for 3D data collection at the Centre for Aquatics Research and Education, University of Edinburgh. Adapted from Sanders (2007[a]).

In contrast to other whole body three-dimensional analysis studies, Psycharakis et al. (2010) and McCabe (2011) used the elliptical zone method (Jensen, 1978), via PC software (Deffeyes & Sanders, 2005) to determine swimmer specific segmental masses and segment mass locations. Although the elliptical zone method relies on the assumption that body segment cross sectional areas can be modelled as ellipses, and that the density data of Dempster (1955) represents that of living tissue, the method estimates body mass within 2% of total body mass (Jensen, 1978). Psycharakis et al. (2010) reported a root mean square error of 1.3% for estimated total body mass, compared to 1.6% for two male and two female jumpers (Sanders, Wilson, & Jensen, 1991) and 1.8% for three prepubescent boys (Jensen, 1978). The accuracy of the elliptical zone method compares well with other mathematical inertia models. For example, Yeadon (1990) reported a maximum error of 2.3% for total body mass estimates for two male and one female gymnast.

No study has used three-dimensional analysis techniques to determine the exact movement patterns of swimmers with a physical impairment, let alone quantify the resultant velocity fluctuation of their centre of masses. Such detailed analyses are crucial for our understanding of how the movements of these swimmers contribute effectively to propulsion and as a consequence their overall forward progression through the water. This is of particular importance for swimmers who are deprived of an important propelling limb, such as single-arm amputees. Work is needed to examine the limb kinematics of unilateral arm amputee front crawl swimmers at different speeds, and how these kinematics relate to forward velocity fluctuations during the stroke cycle. Additional work is needed to examine the limb kinematics of these swimmers in the other three competitive strokes.

2.12 Summary

Within competitive disability swimming each swimmer is unique. Coaches and sport scientists need to understand the subtleties of specific impairments, together with the effect that each has on performance (Keogh, 2011).

Only a small body of scientific literature exists regarding the biomechanical characteristics of well-trained swimmers with a physical disability. In most cases, the literature has focused on the differences between IPC Class, rather than being impairment specific. Across diverse functional impairments, the following research areas have been investigated:

(1) Longitudinal progression in competition performance (Fulton, Pyne, Hopkins, & Burkett, 2009: *n* = 242, IPC Class S2 – S10);

(2) Stroking parameters during 100 m freestyle races (Daly et al., 2003: *n* = 134, IPC Class S2 – S10; Pelayo et al., 1999: *n* = 119, IPC Class S3 – S10);

(3) Arm coordination in front crawl (Satkunskien et al., 2005: *n* = 18, IPC Class S3 – S10);

(4) Limb trajectories (Prins & Murata, 2008: those with amputations, cerebral palsy, paraplegia, quadriplegia and thrombocytopenia);

(5) Passive drag in a prone position (Chatard et al., 1992: *n* = 33, wheelchair users and those walking with and without aids; Fulton et al., 2011: *n* = 12, IPC Class S7 – S10);

(6) Front crawl leg kick (Fulton et al., 2009: *n* = 14, IPC Class S6 – S10; Fulton et al., 2011 *n* = 12, IPC Class S7 – S10).

For highly-trained unilateral arm amputee front crawl swimmers, only race strategy (Burkett & Mellifont, 2008: *n* = 1) and the propulsive contribution of the affected-arm (Lecrivain et al., 2008: *n* = 1; 2010: *n* = 1; Payton & Wilcox, 2006: *n* = 8) have been examined.

The large gaps in the literature emphasise the need for sports scientists to develop the current knowledge base on groups of highly-trained swimmers with the same unique impairment. There is also a need to evaluate the validity of the coaching theories and practices derived from able-bodied swimmers when applied to swimmers with a disability. These needs will be addressed by research that focuses on specific groups of swimmers who have the same unique disability, rather than functional groups containing swimmers with diverse physical impairments. Findings from such applied research will enable coaches of disabled swimmers to make correct and evidence-based decisions when planning practices for their swimmers, thus giving the swimmers the best chance to achieve their potential.

2.13 Academic aims

The general aim of this thesis was to contribute to the body of scientific knowledge regarding the biomechanical characteristics of highly-trained single-arm amputee front crawl swimmers, thus allowing for the application of this knowledge to enhance swimming performance. With this in mind, the thesis focused on three main areas: Firstly, how swimmers adjusted their stroke parameters in order to swim faster and which of the swimmers' anthropometric characteristics were related to performance. Secondly, what inter-arm and leg-to-arm coordination patterns were exhibited by these swimmers and how inter-limb coordination was related to the attainment of maximum swimming speed. Thirdly, what arm movements were used by these swimmers during the front crawl stroke cycle and how these movements contributed to propulsion and as a consequence the overall progression of the swimmers through the water.

The specific academic aims of this thesis were:

1. To determine the relationships between swimming speed, stroke length and stroke frequency and to assess how these stroke parameters related to selected anthropometric characteristics;

2. To examine the effect of swimming speed on inter-arm coordination and the inter-relationships between swimming speed, inter-arm coordination and other stroke parameters;
3. To examine the effect of swimming speed on leg kick and arm stroke coordination;
4. To determine whether upper extremity kinematics differed between sprint- and distance-paced swimming and to examine the inter-relationships between selected upper extremity kinematics and swimming performance;
5. To establish whether intra-cyclic velocity fluctuations differed between sprint- and distance-paced swimming and to determine the influence of the backward velocity of the arms' most distal point on intra-cyclic swimming velocity.

CHAPTER THREE

RELATIONSHIPS BETWEEN STROKE PARAMETERS AND SELECTED ANTHROPOMETRIC CHARACTERISTICS

Published in a modified form as:

Osborough, C., Payton, C., & Daly, D. (2009). Relationships between the front crawl stroke parameters of competitive unilateral arm amputee swimmers, with selected anthropometric characteristics. *Journal of Applied Biomechanics, 25*(4), 304-312.

This chapter determines how, in order to compensate for their missing limb, single-arm amputee swimmers rely on the relative combinations of stroke length and stroke frequency to swim front crawl over a range of speeds. This chapter also assesses which stroking parameters and anthropometric characteristics of these swimmers are important for successful swimming performance. Chapter 3 relates to academic aim 1, in Section 2.13.

3.1 Abstract

The aim of this study was to determine the relationships between swimming speed (SS), stroke length (SL) and stroke frequency (SF) for competitive single-arm amputee front crawl swimmers and to assess how these stroke parameters related to selected anthropometric characteristics. Thirteen highly-trained swimmers (3 male, 10 female) were filmed underwater from a lateral view during seven increasingly faster 25 m front crawl trials. Increases in SS over the 25 m trials were achieved by increases in SF which coincided with decreases in SL. At SS_{max}, inter-swimmer correlations showed that SF was significantly related to SS ($r = .72$; $p < .01$) whereas SL was not. Moderate but non-significant correlations suggested that faster swimmers did not necessarily use longer and slower strokes to swim at a common sub-maximal speed when compared to their slower counterparts. No correlations existed between SL and any anthropometric characteristics. Bi-acromial breadth, shoulder girth and upper-arm length all significantly correlated with the SF used at SS_{max}. These findings imply that as a consequence of being deprived of an important propelling limb, at fast swimming speeds SF is more important than SL in influencing the performance outcome of these single-arm amputee swimmers.

3.2 Introduction

Swimming speed is the product of stroke length (SL) and stroke frequency (SF), such that for a given swimming speed, any change in SF will bring about an inverse change in SL (Craig & Pendergast, 1979). Many investigators have examined the relationships between swimming speed, SF and SL under varying conditions, particularly for competitive able-bodied front crawl swimmers. Under experimental conditions, these swimmers are able to increase their swimming speed by a combination of increasing SF and decreasing SL (Craig & Pendergast, 1979; Hay, 2002; Keskinen & Komi, 1993; Seifert et al., 2004). Furthermore, those swimmers who are able to attain the fastest speeds are able to use longer and slower strokes to swim at slow speeds, when compared to less quick swimmers (Craig & Pendergast, 1979; Hay, 2002). In competition, more successful swimmers use longer SLs (Arellano et al., 1994; East, 1970) than their less successful counterparts and males who are faster than females achieve higher speeds using longer SLs (Arellano et al., 1994; Kennedy et al., 1990; East, 1970; Pelayo et al., 1996). Fastest swimmers who are often taller (Arellano et al., 1994; Kennedy et al., 1990; Pelayo et al., 1996), might be able to apply higher propulsive forces during each stroke cycle (East, 1970) and might do so for a longer time period due to a longer hand path trajectory, when compared to shorter swimmers. Alternatively, they might use a higher proportion of their power output to overcome drag while at the same time expend less power in moving water backwards (Toussaint, 1990), compared to their slower counterparts. For these reasons, SL and body size are recognised as important determinants for success in able-bodied front crawl swimming.

The performance characteristics of competitive front crawl swimmers with a disability have received much less attention from researchers than able-bodied swimmers. Chatard et al. (1992) showed that the degree of physical disability strongly influences the magnitude of the passive drag experienced by swimmers with a disability and also their 100 m and 400 m swim performances. Daly et al. (2003) and Pelayo et al. (1999) concluded that swimmers across a range of disability groups showed certain similarities with able-bodied swimmers. In particular, SL was more related to swimming speed than was SF. Furthermore, these authors showed that while SF was not different between different disability groups and between able-bodied swimmers, SL and swimming speed decreased with an increase in the severity of a swimmer's disability. However, these studies grouped the swimmers according to the international "Functional Classification System" under which persons with diverse impairments compete in the same class. For example, in the current International Paralympic Committee S9 class for front crawl, a unilateral elbow-level arm amputee might compete against a double leg below-knee amputee and a walking paraplegic in the same race. It is likely therefore that as a result of their particular impairment, swimmers within a class might use different combinations of SL and SF to attain a given swimming speed. To date, there has been no examination of the SL, SF and swimming speed relationships for a homogenous group of highly-trained swimmers with the same physical impairment.

Competitive swimmers with a single, elbow-level amputation are clearly disadvantaged when compared to able-bodied swimmers, as they are deprived of an important propelling surface. Especially since the hand plus forearm segment is seen as the major propelling surface responsible for more than 85% of the total propulsion in able-bodied front crawl swimming (Toussaint & Beek, 1992). Payton et al. (2002) showed that the velocity at which these segments move relative to the water is an important determinant for successfully generating propulsion, while Grimston and Hay (1986) suggested that having large muscles in the upper-region of the torso should lead to large force generation during the propulsive phase whilst stroking. With long arms and large hands this large force could be applied effectively to the water, which would increase SL and in turn swimming speed. Without this important propelling surface (i.e. hand plus forearm segment) it seems logical that SL would be compromised. What is less clear however is: (1) how unilateral arm amputee swimmers rely on the SL and SF combination over a range of swimming speeds, in order to compensate for their missing limb; and (2) within this specific group of impaired swimmers, which stroking parameters and anthropometric characteristics are important determinants for successful performance.

The aim of this study was to determine the relationships between swimming speed, SL and SF for competitive unilateral arm amputee front crawl swimmers and to assess how these stroke parameters related to selected anthropometric characteristics. Since the fastest and often the tallest and broadest able-bodied swimmers have the longest SLs and they are able to increase their swimming speed by increasing SF, it would be expected that single-arm amputee front crawl swimmers would be similar in nature. The hypotheses of this study were: (1) over a range of swimming speeds, increases in SS would be achieved by increases in SF; (2) at SS_{max}, SL would be related to SS; (3) SL would be related to selected anthropometric characteristics.

3.3 Methods

3.3.1 Participants

Thirteen (3 male and 10 female) competitive swimmers (age 16.9 ± 3.1 yrs; height 1.69 ± 0.09 m; mass 63.6 ± 13.0 kg), whose mean long course 50 m front crawl personal best time was 32.7 ± 3.1 seconds, participated in this study. The best times of the three male participants were ranked between 24th and 30th in the world for the long course 50 m front crawl (International Paralympic Committee, 2008). For the same event, three of the female participants were ranked between 5th and 12th in the world and four were ranked between 38th and 45th in the world. The best times of the remaining three females were ranked outside the top 60 in the world.

All the participants were single-arm amputees, at the level of the elbow (Appendix 1). Twelve of the swimmers competed in the International Paralympic Committee S9 Class for front crawl; one male swimmer competed in the S8 Class due to an additional impairment of one of his lower limbs. The procedure for the data collection was approved by the Institutional Ethics Committee. All participants provided either written informed consent or, in the case of minors, parental written consent before taking part in the study.

3.3.2 Data Collection

After a standardised 600 m warm up, participants were randomly allocated into one of two test groups. Each participant within each group completed seven 25 m front crawl trials, from a push start, at intervals of 3 minutes, in a counterbalanced fashion (e.g., group 1: from slow to maximum swimming speed; group 2: from maximum to slow swimming speed). To control for the effects of the breathing action on the swimming stroke, participants were instructed not to take a breath through a 10 m test section of the 25 m pool.

Two digital video camcorders (Panasonic NVDS33), sampling at 50 Hz with a shutter speed of 1/350 s were used to film the participants. Each of the camcorders was enclosed in a waterproof housing suspended underwater from one of two trolleys that ran along the side of the pool, parallel to the participants' swimming direction. Each camcorder was adjusted so that the whole body of each participant was visible. This set-up enabled the participants to be filmed under the water, from opposite sides, over the 10 m test section of the pool (Figure 3.1). To scale the recorded video footage a calibration rope, with markers every metre, was suspended horizontally in the water directly beneath the participant. Operators pulled the trolleys at the same speed as the participants, keeping the participant's hip joint marker in the centre of the field of view.

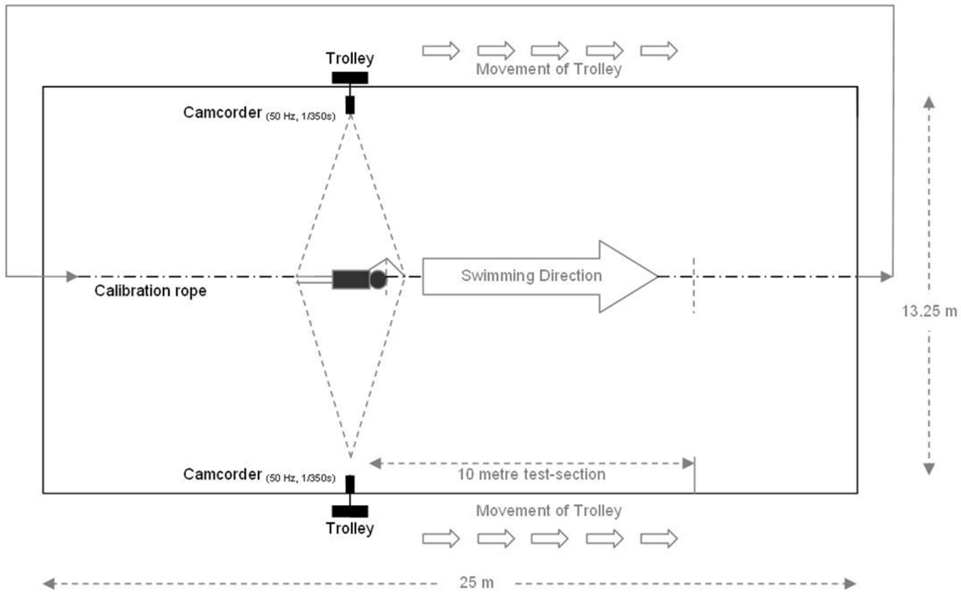


Figure 3.1. Experimental set-up of the swimming test protocol and video recording procedure.

3.3.3 Data Processing

The digital video footage was transferred to a laptop computer and analysed using SIMI Motion 7.2 software (SIMI Reality Motion Systems GmbH, Unterschleißheim, Germany). Three consecutive, non-breathing stroke cycles, for each participant, were then selected for analysis. A stroke cycle was defined from the entry of the hand of the unaffected arm to the next entry of that hand. The following variables were then calculated from the video recordings at 75%, 80%, 85%, 90%, 95% and 100% of each participant's maximum swimming speed (SS_{max}): 1) *Stroke length* (SL) / m: distance that the participant's hip joint marker travelled down the pool with one stroke cycle, calculated as the mean of three stroke cycles; 2) *Stroke frequency* (SF) / Hz: number of stroke cycles performed in one second, calculated as the mean of three stroke cycles; 3) *Swimming speed* (SS) / $m \cdot s^{-1}$: mean forward speed of the participant over three stroke cycles. Using the procedure outlined by Hay (2002), the primary factor was then determined, to identify whether SL or SF made the greater contribution to the change in swimming speed from 75 to 100% of SS_{max}. Mean absolute percentage errors were calculated, as described by Seifert and Chollet (2010), between the group quadratic model and each swimmer's model, for the SS versus SL and for the SS versus SF curves.

3.3.4 Anthropometric Measurements

On the same day as the swimming trials, anthropometric measurements were also recorded. After measurement of body height and body mass, selected anthropometric characteristics were measured using an inelastic measuring tape. Shoulder girth was measured at the maximum circumference of the deltoid muscles inferior to each acromion with the participant's arms hanging freely. Upper-arm girth for both the affected and unaffected limbs was measured at the point of maximum girth with the participant's arm flexed at 90 degrees. Upper-arm length for both the affected and unaffected limbs was measured as the length from the most lateral point on the superior surface of the acromion process to the posterior surface of the olecranon process of the ulna. Bi-acromial breadth was measured between the most lateral point of the acromial processes of the shoulders using a sliding anthropometric caliper.

3.3.5 Statistical Analyses

Means and standard deviations were computed for all the measured variables. Normal distribution of the data was verified using the Shapiro-Wilks test. A dependent *t*-test was used to examine the change in swimming speed between 75 and 100% of SS_{max}. Two separate forward stepwise multiple regression analyses were used between SS_{max} and the SL and SF used at SS_{max}, and between SS_{max} and the SL and SF used at a common sub-maximal swimming speed: 1.1 $m \cdot s^{-1}$ ($SS_{1.1}$). Selected anthropometric variables were correlated with the following parameters: SL_{SSmax} (SL used at SS_{max}); SF_{SSmax} (SF used at SS_{max}); $SL_{SS1.1}$ (SL used to swim at 1.1 $m \cdot s^{-1}$); and $SF_{SS1.1}$ (SF used to swim at 1.1 $m \cdot s^{-1}$). When normal distribution was met the Pearson Product correlation test was used, when not the Spearman Rank correlation test was used. Separate Independent *t*-tests were used to compare the significance of statistical differences between the participant's affected and unaffected sides for relevant anthropometric variables. In all comparisons, the level of significance was set at $p < .05$.

3.4 Results

The mean and standard deviations for swimming speed, SF and SL, from 75 to 100% of SS_{max}, are presented in Table 3.1. Between the first swim at 75% of SS_{max} and last swim at 100% of SS_{max}, mean swimming speed and mean SF significantly increased ($p < .01$) while mean SL showed a non-significant decrease. It should be noted that three of the female participants did not perform at speeds less than or equal to 75% of their SS_{max} and one swimmer did not swim at less than or equal to 80% of her SS_{max}. A similar problem was reported by Hay (2002). Participants were often reluctant to perform or had difficulty performing at speeds far below their normal competition speed. It is likely that this was also the case in this study.

The shape of the mean SS versus SL curve sloped downward, while the mean SS versus SF curve sloped upward (Figure 3.2). Although the shapes of these mean curves were concave (SS versus SL) and convex (SS versus SF), inspection of the individual curves (Appendix III) revealed that some were linear in nature. The inter-individual mean error (Seifert & Chollet, 2010) for the SS versus SL curve was 6.4 % (maximum error: 13.4%; minimum error: 1.0%). For the SS versus SF curve, the inter-individual mean error was 27.2% (maximum error: 39.8%; minimum error: 1.9%). For the increase in swimming speed, from 75 to 100% of SS_{max}, on average SF increased by 5% and SL decreased by 2%. Individual swimmer's SS versus SL and SS versus SF curves can be found in Appendix III.

Table 3.1. Means (M) and standard deviations (SD) of swimming speed, stroke length and stroke frequency for male and female front crawl swimmers.

Gender	% of SS_{max}	Swimming speed ($m \cdot s^{-1}$)		Stroke Length (m)		Stroke Frequency (Hz)	
		M	***SD***	***M***	***SD***	***M***	***SD***
Males	100	1.54	0.09	1.64	0.17	0.94	0.08
(*n* = 3)	95	1.46	0.09	1.69	0.17	0.87	0.06
	90	1.39	0.08	1.74	0.17	0.80	0.04
	85	1.31	0.08	1.77	0.21	0.74	0.05
	80	1.23	0.07	1.79	0.19	0.69	0.05
	75	1.16	0.07	1.79	0.20	0.65	0.06
Females	100	1.31	0.10	1.67	0.17	0.79	0.09
(*n* = 10)	95	1.24	0.09	1.71	0.15	0.73	0.08
	90	1.17	.09	1.73	0.14	0.68	0.07
	85	1.11	0.08	1.77	0.13	0.63	0.06
	80	1.06	0.07	1.78	0.14	0.60	0.06
	75	1.00	0.07	1.82	0.13	0.55	0.06
Group mean	100	1.36	0.14	1.66 [a]	0.16	0.82 [b]	0.11
(*n* = 13)	95	1.29	0.13	1.71 [a]	0.15	0.76 [b]	0.09
	90	1.22	0.12	1.73 [a]	0.14	0.71 [b]	0.08
	85	1.16	0.12	1.77 [a]	0.14	0.66 [b]	0.08
	80	1.10	0.10	1.78 [a]	0.15	0.62 [b]	0.07
	75	1.05	0.10	1.81 [a]	0.14	0.58 [b]	0.07

[a] Using the group mean quadratic equation $y = -0.00009x^2 + 0.0096x + 1.5847$, SL had a percentage change of -1.7 % from 75 to 100% of SS_{max}.

[b] Using the group mean quadratic equation $y = 0.0001x^2 - 0.0122x + 0.7952$, SF had a percentage change of 4.8 % from 75 to 100% of SS_{max}.

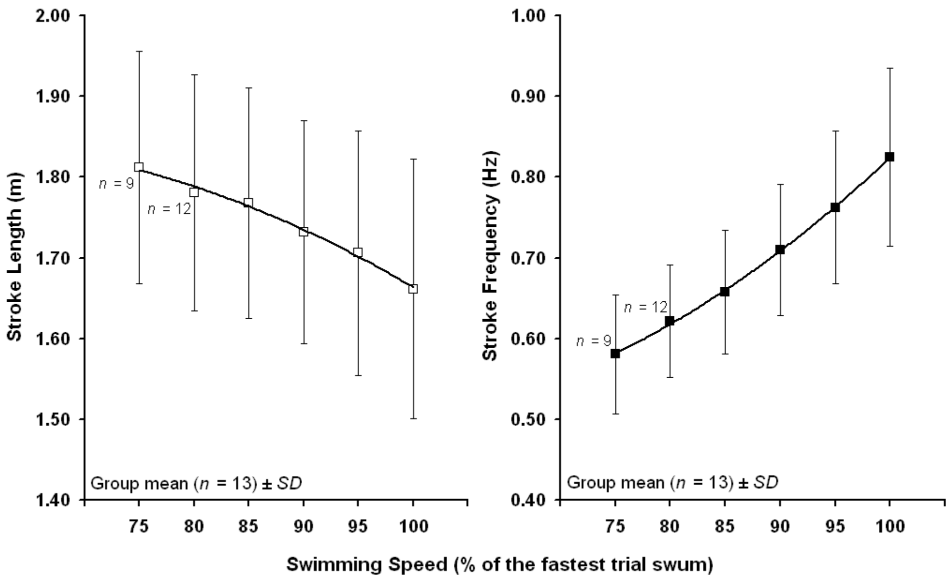


Figure 3.2. Changes in SL and SF (mean ± SD) with an increase in swimming speed (expressed as a percentage of the maximum swimming speed recorded).

The SLs and SFs used at SS_{max} and at $SS_{1.1}$ are shown in Table 3.2. Inter-swimmer correlations (Figure 3.3) showed that SF_{SSmax} was significantly related to SS_{max} ($r = .72$; $p < .01$) whereas SL_{SSmax} was not ($r = .01$). The results from the forward stepwise multiple regression analysis revealed that the predictors SF_{SSmax} and SL_{SSmax} accounted for 98% of the total variance in SS_{max}. SF_{SSmax} had the larger influence, accounting for 52% of the variance in SS_{max} while SL_{SSmax} accounted for 46%. As shown in Figure 3.4, there were non-significant moderate correlations between SS_{max} and $SL_{SS1.1}$ ($r = .38$) and between SS_{max} and $SF_{SS1.1}$ ($r = -.37$).

Table 3.2. Means (M) and standard deviations (SD) of stroke lengths and stroke frequencies used at SS_{max} and at 1.1 m·s^{-1} for male and female front crawl swimmers.

Gender	At 100% of SS_{max}				At 1.1 m·s^{-1}			
	Stroke Length (m)		Stroke Frequency (Hz)		Stroke Length (m)		Stroke Frequency (Hz)	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Males (*n* = 3)	1.64	0.17	0.94	0.08	1.84	0.24	0.60	0.08
Females (*n* = 10)	1.67	0.17	0.79	0.09	1.76	0.14	0.63	0.05
Group (*n* = 13)	1.66 [a]	0.16	0.82 [b]	0.11	1.78	0.16	0.62	0.05

[a] Correlation between SS_{max} and predictors: SL_{SSmax}, SF_{SSmax} statistically significant (r = .99; R^2 = .98; p < .01).

[b] Correlation between SS_{max} and SF_{SSmax} statistically significant (r = .72; R^2 = .52; p < .01).

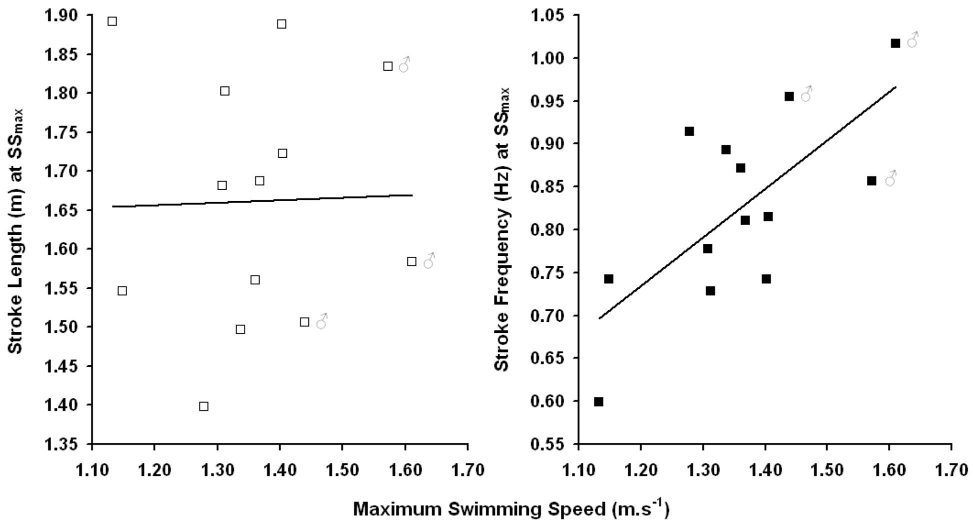


Figure 3.3. Inter-swimmer correlations; left-hand side: SL_{SSmax} versus SS_{max} (r = .01); right-hand side: SF_{SSmax} versus SS_{max} (r = .72; p < .01).

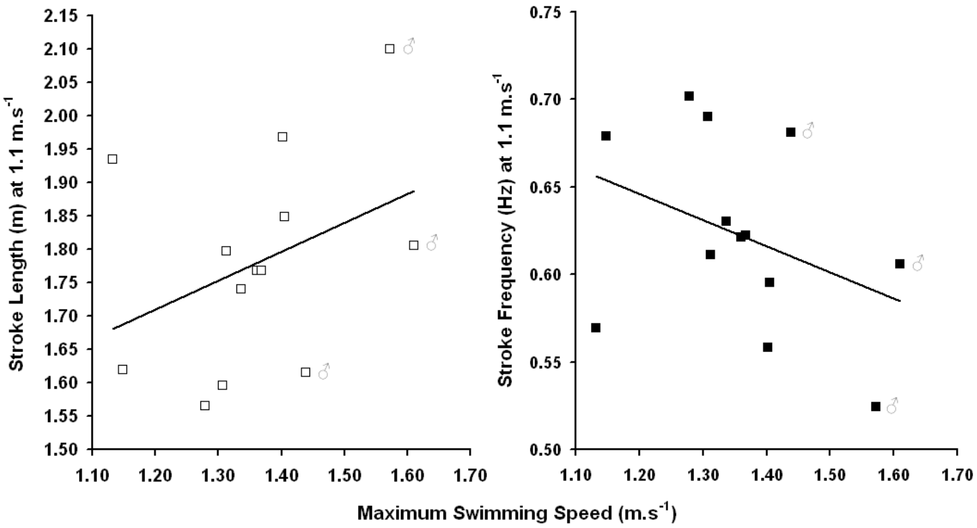


Figure 3.4. Inter-swimmer correlations; left-hand side: $SL_{SS1.1}$ versus SS_{max} (r = .38); right-hand side: $SF_{SS1.1}$ versus SS_{max} (r = -.37).

The means and standard deviations of the anthropometric characteristics are presented in Table 3.3. The male swimmers were on average 0.18 m taller and 20.6 kg heavier than the female swimmers. The males' mean shoulder girth and bi-acromial breath were 0.15 m and 0.04 m larger respectively than the females. Similarly, the males' mean upper-arm girth and length were greater than that of the females.

The group's mean affected upper-arm girth (0.24 ± 0.02 m) was significantly smaller ($p < .01$) than that of the unaffected arm (0.29 ± 0.03 m). The difference in the group's mean upper-arm length between the arms was not significant (0.31 ± 0.02 m vs. 0.31 ± 0.02 m).

There were significant relationships between bi-acromial breadth and SF_{SSmax} (r = .86; $p < .01$), between shoulder girth and SF_{SSmax} (r = .64; $p < .01$) and between upper-arm length and SF_{SSmax} (r = .58; $p < .05$). No relationships existed between SL, both at SS_{max} and at $SS_{1.1}$, and any anthropometric characteristics. Similarly, no relationships existed between $SF_{SS1.1}$ and any of the anthropometric characteristics measured.

Table 3.3. Means (M) and standard deviations (SD) of anthropometric characteristics for male and female swimmers.

Gender	Body height (m)		Body mass (kg)		Shoulder girth (m)	
	M	***SD***	***M***	***SD***	***M***	***SD***
Males (n = 3)	1.83	0.03	79.40	17.18	1.11	0.06
Females (n = 10)	1.65	0.04	58.82	7.12	0.96	0.05
Group mean (n = 13)	1.69	0.09	63.57	12.99	1.00 [a]	0.08

Gender	Bi-acromial breadth (m)		Upper-arm girth (m)		Upper-arm length (m)	
	M	***SD***	***M***	***SD***	***M***	***SD***
Males (n = 3)	0.40	0.02				
Affected Arm			0.26	0.01	0.34	0.01
Unaffected Arm			0.33	0.02	0.33	0.02
Females (n = 10)	0.36	0.01				
Affected Arm			0.24	0.02	0.31	0.02
Unaffected Arm			0.28	0.02	0.30	0.01
Group mean (n = 13)	0.37 [b]	0.02				
Affected Arm			0.24 [d]	0.02	0.31	0.02
Unaffected Arm			0.29 [d]	0.03	0.31 [c]	0.02

[a] Correlation between SF_{SSmax} and shoulder girth statistically significant (r = .64; p < .01).

[b] Correlation between SF_{SSmax} and bi-acromial breadth statistically significant (r = .86; p < .01).

[c] Correlation between SF_{SSmax} and upper-arm length statistically significant (r = .58; p < .05).

[d] Difference between affected and unaffected arm statistically significant (p < .01).

3.5 Discussion

The aim of this study was to determine the relationships between swimming speed, SL, and SF for competitive unilateral arm amputee front crawl swimmers and to assess how these stroke parameters related to selected anthropometric characteristics. The first hypothesis was accepted; over a range of swimming speeds, increases in SS were achieved by increases in SF. The second hypothesis was rejected; at SS_{max}, SL was not related to SS. The third hypothesis was rejected; SL was not related to selected anthropometric characteristics.

The arm amputee swimmers in this study achieved progressive increases in swimming speed (above 75% of SS_{max}) by increasing SF. The increase in SF coincided with a decrease in SL, this being similar for able-bodied front crawl swimmers (Keskinen & Komi, 1993; Seifert et al., 2004). The mean SS versus SL and mean SS versus SF curves had similar characteristics as those reported for able-bodied front crawl swimmers (Craig & Pendergast, 1979; Hay, 2002), with the increase in SF contributing to the increase in swimming speed above 75% of SS_{max}. However, as the data did not extend to swimming speeds lower than 75% of SS_{max} it was not possible to determine whether SL was the primary factor at low swimming speed, which is the case for able-bodied swimmers.

The mean SS_{max} achieved by the male amputees was higher than that reported by Pelayo et al. (1999) for top-level male S9 front crawl swimmers during a competitive 100 m race (1.54 vs. 1.49 $m \cdot s^{-1}$). The female amputees' mean SS_{max} was also higher than that of the top-level female S9 100 m front crawl competitors in the Pelayo et al. (1999) study (1.31 vs. 1.27 $m \cdot s^{-1}$). The male amputees used shorter and faster strokes to attain their SS_{max}, than the male S9 100 m competitors (1.64 vs. 1.72 m for SL; 0.94 vs. 0.87 Hz for SF). The female amputees however, used longer and slower strokes to swim maximally when compared to the female S9 competitors (1.67 vs. 1.49 m for SL; 0.79 vs. 0.88 Hz, for SF).

In comparison to able-bodied competitors, the SS_{max} of both the male and female amputees was substantially slower than that of able-bodied 100 m competitors (e.g., 1.83 $m \cdot s^{-1}$ and 1.61 $m \cdot s^{-1}$ for males and females respectively; Pelayo et al., 1999). The male amputees had a higher SF, while the female amputees had a similar SF when compared to these able-bodied competitors (0.83 Hz and 0.81 Hz for able-bodied males and females respectively). Both the male and female amputees had appreciably shorter SLs, when again compared to these able-bodied swimmers (2.21 m and 2.00 m for able-bodied males and females respectively). These differences can be attributed to the physical impairment of the amputees but might also be influenced by the distances being swum and the relatively small stature of the amputee swimmers.

In this study, the mean $SL_{SS1.1}$ and mean $SF_{SS1.1}$ used by the amputees were higher and lower respectively, than those reported by Payton and Wilcox (2006) for similarly-trained unilateral arm amputees during arms-only swimming at 1.09 $m \cdot s^{-1}$ (1.78 vs. 1.45 m for SL; 0.62 vs. 0.75 Hz for SF). Much of this discrepancy may be accounted for by the fact that swimmers in the Payton and Wilcox (2006) study did not use a leg kick. Mean $SL_{SS1.1}$ was substantially lower and mean $SF_{SS1.1}$ higher than that reported by Craig and Pendergast (1979) for trained able-bodied swimmers swimming at 1.1 $m \cdot s^{-1}$ (1.78 vs. 2.12 m for SL; 0.62 vs. 0.52 Hz for SF). Being deprived of an important propelling limb and the possibility that the amputee swimmers in this study were not as technically proficient as those tested by Craig and Pendergast (1979) would account for the observed differences in the stroke parameters between the amputee and able-bodied front crawl swimmers. Similar differences have been reported between adult and child swimmers (Kjendlie, Stallman, & Stray-Gundersen, 2004) and when swimming with and without paddles (Toussaint & Beek, 1992).

There were moderate but non-significant correlations between SS_{max} and $SL_{SS1.1}$ and between SS_{max} and $SF_{SS1.1}$. This suggests that the faster amputee swimmers in the group did not necessarily use longer and slower strokes, to swim sub-maximally, than their slower counterparts. This finding contrasts with that for able-bodied front crawl swimmers. Craig and Pendergast (1979) reported that the fastest front crawl swimmers had the longest and slowest strokes at sub-maximal swimming speeds.

The significant correlation between SS_{max} and SF_{SSmax} indicates that the faster amputee swimmers used higher SFs, compared to their slower counterparts. Interestingly, there was no inter-swimmer correlation between SS_{max} and SL_{SSmax}. These are key findings, as they are in contrast with what has been reported previously. In the literature there is agreement that more successful able-bodied front crawl swimmers are characterised by longer strokes (Arellano et al., 1994; Craig & Pendergast, 1979; East, 1970), as are disabled swimmers with a limited impairment (Daly et al., 2003; Pelayo et al., 1999). In the current study, this was not the case. The findings imply that to improve their maximum swimming speed, unilateral arm amputees should focus on increasing their SF, rather than swimming with the longest possible SL. Thus, at fast swimming speeds, SF is more important than SL in influencing short-term performance outcomes (e.g., during a 50 m sprint). SL should not be completely ignored however, as technical improvements in a swimmer's performance over a longer-term should be reflected in their ability to swim at a given speed with a longer SL.

Body size has also been suggested to be an important determinant for success in able-bodied front crawl swimming (Grimston & Hay, 1986). Wells et al., (2006) presented detailed normative data on the physical characteristics of Canadian National Team swimmers between the ages of 12 and 18 years. The unilateral arm amputees in this study, when compared to the these able-bodied swimmers of the same chronological age, were of similar body height and body mass (1.83 vs. 1.84 m and 79.4

vs. 77.6 kg for males; 1.69 vs. 1.68 m and 58.8 vs. 60.5 kg for females; data reported for arm amputee and able-bodied swimmers respectively). The unaffected upper-arm girth of the amputees was also comparable to that of these able-bodied swimmers (0.33 vs. 0.34 m for males; 0.28 vs. 0.29 m for females). However, the affected upper-arm girth of the amputees was significantly smaller than that of the unaffected arm. This can be attributed to less muscle mass on the affected limb and is a likely result of reduced loading on the biceps and triceps muscles above the amputation leading to less muscle hypertrophy, when compared to the unaffected arm. The amputees' bi-acromial breadth was also similar to that of the Canadian swimmers (0.40 vs. 0.41 m for males; 0.36 vs. 0.38 m for females). Since the amputee swimmers showed similar anthropometric characteristics to able-bodied swimmers, one might expect the stroke-anthropometric characteristic relationships that exist for able-bodied swimmers (e.g., Grimston & Hay, 1986; Pelayo et al., 1996) to also exist for these amputee swimmers.

Unlike able-bodied front crawl swimmers however, there were no relationships between SL, both at SS_{max} and $SS_{1.1}$, and any of the anthropometric characteristics measured. Instead there were significant relationships between bi-acromial breadth, between shoulder girth, and between upper-arm length, and SF_{SSmax}. The arm amputee swimmers in the group who had broader shoulders and longer arms did not use longer SLs at SS_{max}; rather they used higher SFs, when compared to their more slender counterparts. This is in contrast to able-bodied swimmers. Able-bodied front crawl swimmers who are taller (Pelayo et al., 1996), with longer limbs and a larger cross-sectional area of the upper-torso (Grimston & Hay, 1986) use longer SLs and lower SFs when compared to smaller, less successful swimmers (Arellano et al., 1994).

Grimston and Hay (1986) argued that able-bodied swimmers with broad shoulders would likely have large muscles in the upper-region of the torso responsible for shoulder extension. These authors suggested that with long arms and large hands an able-bodied swimmer might be able to transfer the force generated by these muscles more effectively to the water, when compared to a swimmer with shorter and smaller limbs. As a larger propelling surface is directly related to propelling efficiency (Toussaint & Beek, 1992), these taller, broader and longer-limbed swimmers would have an increased SL for a given swimming speed, when compared to physically smaller swimmers. This does not appear to be the case for unilateral arm amputee front crawl swimmers. As a consequence of being deprived of an important propelling limb, the expected relationships that exist for able-bodied swimmers (e.g., Grimston & Hay, 1986; Pelayo et al., 1996) do not exist for front crawl swimmers with a single-arm amputation.

In this study, the broader swimmers in the group were able to attain faster swimming speeds using higher SFs, when compared to their more slender and slower counterparts. It might be expected that the fastest swimmers who exhibited the highest SFs might pull their affected limb through the water the quickest. However, Payton and Wilcox (2006) showed this not to be the case. These authors reported that for unilateral arm amputees, the increase in intra-cyclic swimming speed observed during the pull phase of the affected arm did not correlate with the shoulder extension velocity of the same arm. The authors concluded that factors other than limb speed, such as the timing and trajectory of the pull, may be more important in determining the effectiveness of the pull. As in the Payton and Wilcox (2006) study, the amputee swimmers in this study also demonstrated a variety of different timings and limb trajectories during the underwater phase of the arm stroke cycles. Further study is needed to ascertain whether some of these timings and trajectories are more conducive to attaining higher SFs and ultimately more successful swimming performance than others.

3.6 Summary and Conclusion

The results from this study show that increases in swimming speed (above 75% of SS_{max}) were achieved by increasing SF which coincided with a decrease in SL. At SS_{max}, inter-swimmer correlations showed that SF was significantly related to SS_{max} whereas SL was not. Faster swimmers did not necessarily use longer and slower strokes to swim at a common sub-maximal speed when compared to their slower counterparts. No relationships existed between SL and any anthropometric characteristics, instead bi-acromial breadth, shoulder girth and upper-arm length were all significantly related to the SF used at SS_{max}. These findings imply that as a consequence of being deprived of an important propelling limb, at fast swimming speeds SF is more important than SL in influencing the performance outcome of highly-trained front crawl swimmers with a single-arm amputation.

CHAPTER FOUR

EFFECT OF SWIMMING SPEED ON INTER-ARM COORDINATION

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This chapter examines whether the inter-arm coordination of single-arm amputees changes with a change in front crawl swimming speed. In addition to this, this chapter examines the inter-relationship between swimming speed, inter-arm coordination and other stroke parameters, within this specific group of impaired swimmers. Chapter 4 relates to academic aim 2, in Section 2.13.

4.1 Abstract

The aim of this study was to examine the effect of swimming speed on inter-arm coordination and the inter-relationships between swimming speed, inter-arm coordination and other stroke parameters, in a group of competitive unilateral arm amputee front crawl swimmers. Thirteen highly-trained swimmers were filmed underwater during a series of 25 m front crawl trials of increasing speed. Arm coordination for both arms was quantified using an adapted version of the Index of Coordination. Inter-arm coordination of the amputee swimmers did not change as swimming speed was increased up to maximum. Swimmers showed significantly more catch-up coordination of their affected-arm compared to their unaffected-arm. When sprinting, the fastest swimmers used higher stroke frequencies and less catch-up of their affected-arm, than the slower swimmers. Unilateral arm-amputees use a strategy for asymmetrical coordinating their affected-arm relative to their unaffected-arm to maintain the stable repetition of their overall arm stroke cycle. When sprinting, the attainment of a high stroke frequency is influenced mainly by the length of time the affected-arm is held in a stationary position in front of the body before pulling. Reducing this time delay appears to be beneficial for successful swimming performance.

4.2 Introduction

Success in competitive swimming depends on a swimmer's ability to maximise propulsion and minimise resistance. In able-bodied front crawl swimming, where the two arms move rhythmically in an anti-phase inter-limb relationship (Nikodelis et al., 2005), the hand plus forearm segment is seen as the major propelling surface responsible for about 85% of the total propulsion (Toussaint & Beek, 1992). Not all of the front crawl arm stroke action is propulsive however. The Recovery, Entry and Catch are recognised to be non-propulsive phases within the stroke cycle (Chollet et al., 2000; Maglischo et al., 1988). When considering the effectiveness of a swimmer's technique, understanding how the propulsive and non-propulsive phases of the two arms are coordinated is crucial.

Many studies have used the Index of Coordination (IdC) to examine the arm coordination of competitive able-bodied swimmers under various conditions. The IdC, as described by Chollet et al. (2000), conforms to one of three major models: (1) *Catch-up* describes a time delay between the propulsive phases of the two arms (i.e. IdC < 0); (2) *Opposition* describes a continuous series of propulsive actions: one arm begins the Pull phase when the other is finishing the Push phase (i.e. IdC = 0); (3) *Superposition* describes an overlap, to a greater or lesser extent, of the propulsive phases (i.e. IdC > 0). There is agreement that able-bodied swimmers modify their arm coordination with increases in swimming speed (Chollet et al., 2000; Potdevin et al., 2006; Seifert et al., 2004). Such changes coincide with an increase in stroke frequency. Arm coordination has been shown to vary between different performance levels (Chollet et al., 2000; Millet et al., 2002; Seifert et al, 2007). The fastest front crawl swimmers are generally characterised by higher IdC values (opposition and superposition) when compared to their slower counterparts, who tend more towards catch-up. Higher IdC values have been shown to correlate significantly with higher stroke frequencies (Chollet et al., 2000; Seifert et al., 2004). Differences in arm coordination between genders have also been reported (Seifert, Boulesteix, & Chollet, 2004; Seifert et al., 2005).

An examination of the arm coordination of competitive front crawl swimmers with a disability has received much less attention from researchers than that given to able-bodied swimmers. Presently, only Satkunskiene et al. (2005) appear to have addressed this specific research area. Within a group of well-trained swimmers with diverse loco-motor disabilities, these authors showed that swimmers across a range of impairment groups exhibited certain similarities with able-bodied swimmers. In particular, the "more-skilled" swimmers were characterised by their ability to overlap the propulsive phase of one arm with the propulsive phase of the other and attain higher stroke frequencies, when compared to "less-skilled" swimmers. It was acknowledged however, that large variations existed between the disabled swimmers' stroking techniques. These were attributed to the diverse functional impairments of the swimmers.

Competitive swimmers with a single, elbow-level amputation are clearly impaired when compared to able-bodied swimmers, as they are deprived of an important propelling surface (i.e. hand plus forearm segment). If these body segments are missing, swimmers must rely on the surface area of the existing limb to generate propulsion (Prins & Murata, 2008). Prins and Murata (2008) presented a kinematic analysis of a single, female unilateral arm amputee swimmer (site of impairment unknown). Although the amputee was likely to be a recreational swimmer, these authors identified a key feature of her arm stroke technique. At the point when the affected-arm entered the water it distinctly paused, whereas the unaffected-arm did not. These authors reasoned that this delay (25% of total stroke time) maintained the stable rhythm of the swimmer's overall arm stroke cycle. Such a tentative finding highlights the possibility that a unilateral arm amputee's affected- and unaffected-arm might have different roles within the stroke cycle. The primary function of the unaffected-arm might be to generate propulsion while the affected-arm might simply function to control inter-arm asymmetry. However, it needs to be established whether this asymmetrical inter-arm coordination is purely a feature of one recreational swimmer or whether it is a common feature for all unilateral arm amputees, including competitive swimmers, over a range of swimming speeds.

The aim of this study was to examine the effect of swimming speed on inter-arm coordination and the inter-relationships between swimming speed, inter-arm coordination and other stroke parameters, in a group of competitive unilateral arm amputee front crawl swimmers. Given that single-arm amputees increase their swimming speed by increasing stroke frequency (Osborough, Payton & Daly 2009) and that for able-bodied swimmers, changes in arm-coordination occur with changes in swimming speed, it would be expected that the former groups' arm coordination would also change as swimming speed increased. Furthermore, it was expected that the single-arm amputees would display similar characteristics to able-bodied swimmers; in that higher IdC values would be related to higher stroke frequencies and swimming speeds. The hypotheses for this study were: (1) inter-arm coordination would change as swimming speed was increased up to maximum; and (2) at sprint speed, higher inter-arm coordination indices would be related to stroke frequency and swimming speed.

4.3 Methods

4.3.1 Participants

Thirteen (3 male and 10 female) competitive swimmers (age 16.9 ± 3.1 yrs; height 1.69 ± 0.09 m; mass 63.6 ± 13.0 kg), whose mean long course 50 m front crawl personal best time was 32.7 ± 3.1 seconds, participated in this study. All the participants were single-arm amputees, at the level of the elbow and were the same as those who participated in Study 1 (Chapter 3). Further details of the participant group can be found in Section 3.3.1. The procedure for the data collection was approved by the Institutional Ethics Committee. All participants provided either written informed consent or, in the case of minors, parental written consent before taking part in the study.

4.3.2 Data Collection

After a standardised 600 m warm up each participant completed seven, self-paced 25 m front crawl trials, from a push start, at intervals of 3 minutes. Seven of the swimmers performed the trials from slow to maximum swimming speed; the rest performed the trials from maximum to slow swimming speed. Participants were requested to swim each trial at a predetermined target pace, based on a percentage of their 50 m front crawl personal best time. All trials were manually recorded by two experienced timekeepers using chronograph stopwatches (Model 898). Any trial that was not close to the predetermined target pace (i.e. within ± 2%) was repeated after a 3 minute rest. To control for the effects of the breathing action on the swimming stroke, participants were instructed not to take a breath through a 10 m test section of the 25 m pool.

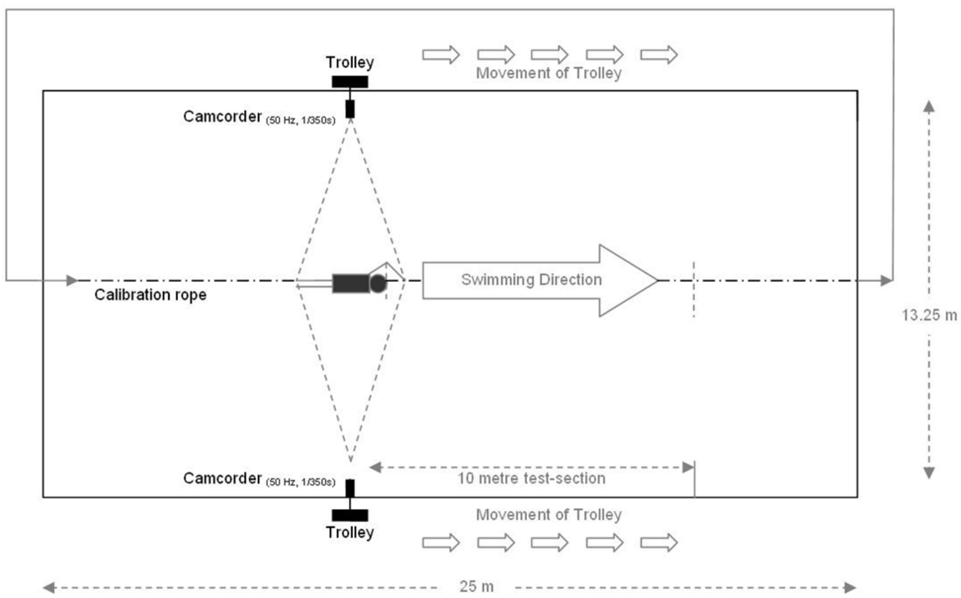

Figure 4.1. Plan view of the two-dimensional filming set-up.

Two digital video camcorders (Panasonic NVDS33), sampling at 50 Hz with a shutter speed of 1/350 s were used to film the participants under the water, from opposite sides, over the 10 m test section of the pool (Figure 4.1). Each of the camcorders was enclosed in a waterproof housing suspended underwater from one of two trolleys that ran along the side of the pool, parallel to the participants' swimming direction. The field of view of each camcorder was adjusted so that the whole body of each participant was visible. To scale the recorded video footage a calibration rope, with markers every metre, was suspended horizontally in the water directly beneath the participant. Operators pulled the trolleys at the same speed as the participants, keeping the participant's hip joint marker in the centre of the field of view.

4.3.3 Data Processing

The digital video footage was transferred to a laptop computer and analysed using SIMI Motion 7.2 software (SIMI Reality Motion Systems GmbH, Unterschleißheim, Germany). Three consecutive, non-breathing stroke cycles (i.e. from the entry of the hand of the unaffected-arm to the fourth entry of that hand), for each participant, were selected for analysis. The estimated locations of the gleno-humeral joint centre and the elbow joint centre of both the affected- and unaffected-arms were digitised at 50 Hz to obtain the angular position of the upper-arms, as a function of time. Upper-arm angle, which was assumed to remain in the swimmer's plane of motion during the underwater stroke, was determined relative to the water surface. The latter was used to establish a true horizontal frame of reference. Before filming, the skin overlaying the joint centres was marked with black pen to help estimate their location.

4.3.4 Arm Coordination and Stroke Phases

The IdC is often used to quantify the arm coordination of able-bodied front crawl swimmers. While being a valuable measurement tool for able-bodied swimmers, problems arise when trying to apply the IdC to swimmers with a single elbow-level arm amputation. Firstly, the IdC uses the hand positions of able-bodied swimmers to define four arm phases of the front crawl stroke cycle. The participants in this study however were missing a hand plus forearm segment. Secondly, the IdC assumes that an able-bodied swimmer generates propulsion during the Pull and Push phases of the arm stroke cycle. Currently, it is uncertain whether, and if so at what point, the affected-arm of a unilateral arm amputee can contribute effectively to propulsion. For these reasons, an adapted version of the Index of Coordination (IdC_{adapt}), which used a common reference point on both arms rather than the onset of propulsion to quantify arm coordination, was utilised in this study. The arm stroke phases of the unilateral arm amputee swimmers were determined from the angle made by the shoulder-to-elbow position vector relative to the horizontal. Similar approaches have been used previously (e.g., Persyn, Hoeven & Daly, 1979; Rouard & Billat, 1990).

Each upper-arm movement was divided into four phases (Figure 4.2): Entry and Glide (A); Pull (B); Push (C); and Recovery (D).

(A) *Entry and Glide*: from where the elbow joint centre entered the water (0°) to where the shoulder-to-elbow position vector made an angle of 25° with the horizontal. This latter position corresponded to a point where typically the swimmers actively initiated extension of their affected-arm.

(B) *Pull*: from the end of the Entry and Glide (25°) to where the shoulder-to-elbow position vector made an angle of 90° with the horizontal.

(C) *Push*: from the end of the Pull (90°) to where the shoulder-to-elbow position vector made an angle of 155° with the horizontal. This latter position corresponded to a point where, as a result of the rolling action of the swimmers' trunk and the bow-wave created by the swimmers' movement through the water, the most-distal part of the swimmers' affected-arm typically exited the water.

(D) *Recovery*: from the end of the Push (155°) to where the elbow joint centre enters the water (360°).

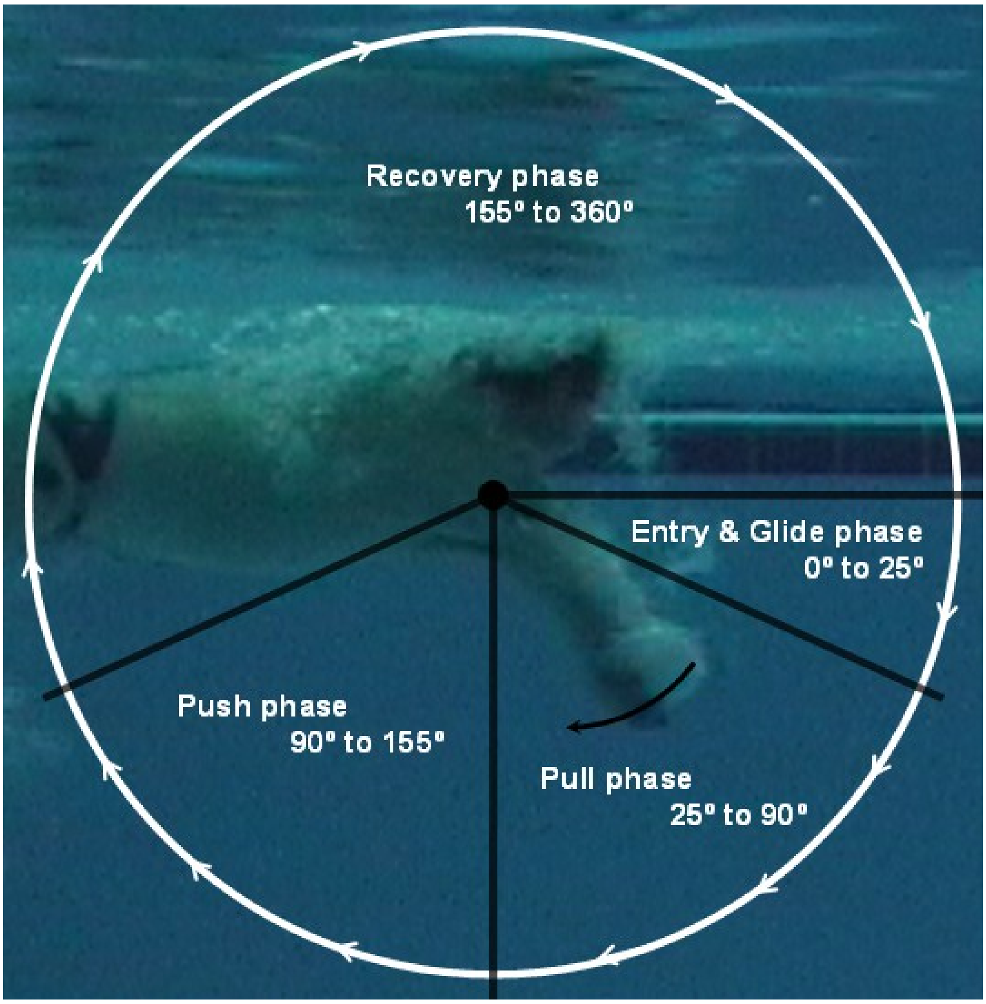

Figure 4.2. Divisions of the arm stroke phases: Entry and Glide (A); Pull (B); Push (C); and Recovery (D) for a unilateral arm amputee front crawl swimmer.

It should be noted that the start of the Pull phase and end of the Push phase, as described above, did not necessarily correspond to the start and end of propulsion.

The time duration of each phase was determined with a precision of 0.02 s from the video recordings, calculated as a mean of three arm stroke cycles. The duration of a complete arm stroke cycle was defined as the sum of the four phases (A + B + C + D).

Each phase was then expressed as a percentage of the duration of the complete arm stroke cycle.

The arm coordination for both the affected (IdC_{af}) and unaffected (IdC_{un}) limbs was determined at 80%, 85%, 90%, 95% and 100% of each participant's maximum swimming speed (SS_{max}). These percentages were determined from the predetermined target-paced swims and, where the trials did not exactly match, by linear interpolation of the two adjacent experimental data points. The lag time between the beginning of the Pull phase with the affected-arm and the end of the Push phase with the unaffected-arm defined IdC_{af} (i.e. arm coordination on the affected side), which was expressed as a percentage of the duration of the complete arm stroke cycle. The lag time between the beginning of the Pull phase of the unaffected-arm and the end of the Push phase with the affected-arm defined IdC_{un} (i.e. arm coordination on the unaffected side), which was expressed as a percentage of the duration of the complete arm stroke cycle.

For comparisons against the literature (e.g., Chollet et al., 2000; Potdevin et al., 2006; Seifert et al., 2004), the IdC_{adapt} was determined. The IdC_{adapt} (%) was the mean of IdC_{af} (%) and IdC_{un} (%). A time delay between the end of the Push phase of one arm and the beginning of the Pull phase of the other indicated *Catch-up* coordination ($IdC_{adapt} < 0\%$). When one arm began the Pull phase as the other was finishing the Push phase, the coordination was *Opposition* ($IdC_{adapt} = 0\%$). When the Pull phase of one arm overlapped with the Push phase of the other, the coordination was *Superposition* ($IdC_{adapt} > 0\%$).

The following stroke parameters were calculated from the video recordings at 80%, 85%, 90%, 95% and 100% of each participant's SS_{max}: *Stroke length* (m) was defined as the distance that the participant's hip joint marker travelled down the pool with one stroke cycle, calculated as the mean of three stroke cycles; *Stroke frequency* (Hz) was defined as the number of stroke cycles performed in one second, calculated as the mean of three stroke cycles; *Swimming speed* ($m \cdot s^{-1}$) was defined as the mean forward speed of the participant over three stroke cycles.

4.3.5 Statistical Analyses

Means and standard deviations were computed for all the measured variables. Normal distribution of the data was verified using the Shapiro-Wilks test. Two separate univariate general linear modeling (GLM) tests were used to compare changes in swimming speed and IdC_{adapt} across the five percentage speed increments. A multivariate GLM test was used to compare the changes between IdC_{af} and IdC_{un} according to the percentage speed increments. Sphericity was assessed by means of the Mauchley test and adjusted via the Greenhouse-Geisser procedure. Multiple comparisons were made with the Bonferroni *post hoc* test. Correlations were calculated among swimming speed, stroke frequency, stroke length, adapted Index of Coordination and the relative durations of the arm stroke phases, for both the affected- and unaffected-arms, at 100% of SS_{max}. Pearson Product correlation tests were used in all comparisons except those related to the unaffected-arm's Entry and Glide and Push phases. As these variables were found to be not normally distributed, Spearman Rank correlation tests were used instead. In all comparisons, the level of significance was set at $p < .05$. Statistical analysis procedures were performed using SPSS 14.0 software.

4.4 Results

The means and standard deviations of swimming speed (SS), the adapted version of the Index of Coordination (IdC_{adpt}) and those of the affected (IdC_{af}) and unaffected (IdC_{un}) arms are presented in Table 4.1.

Table 4.1. Means (M) and standard deviations (SD) of swimming speed (SS), adapted index of coordination (IdC_{adpt}), and index of coordination for both the affected (IdC_{af}) and unaffected (IdC_{un}) arms for front crawl swimmers (male: ♂, female: ♀, group mean: G.M.).

	Percentage of maximum swimming speed (*M* ± *SD*)				
	80	**85**	**90**	**95**	**100**
♂ (*n* = 3)					
SS ($m \cdot s^{-1}$)	1.23 ± 0.07	1.31 ± 0.08	1.39 ± 0.08	1.46 ± 0.09	1.54 ± 0.09
IdC_{adpt} (%)	-15.3 ± 2.1	-14.6 ± 1.2	-16.0 ± 2.2	-16.6 ± 2.0	-15.5 ± 1.4
IdC_{af} (%)	-17.4 ± 6.0	-16.2 ± 7.5	-17.1 ± 8.1	-17.0 ± 6.8	-17.4 ± 5.5
IdC_{un} (%)	-13.2 ± 7.5	-13.0 ± 8.1	-15.0 ± 7.7	-16.2 ± 7.7	-13.7 ± 7.5
♀ (*n* = 10)					
SS ($m \cdot s^{-1}$)	1.06 ± 0.07	1.11 ± 0.08	1.17 ± 0.09	1.24 ± 0.09	1.31 ± 0.10
IdC_{adpt} (%)	-16.9 ± 5.2	-17.2 ± 6.6	-17.7 ± 6.3	-17.7 ± 6.0	-17.8 ± 5.9
IdC_{af} (%)	-27.6 ± 5.3	-27.4 ± 6.1	-26.5 ± 7.0	-26.5 ± 6.1	-27.4 ± 7.0
IdC_{un} (%)	-6.2 ± 9.4	-7.0 ± 10.4	-8.9 ± 9.4	-8.9 ± 8.7	-8.1 ± 8.5
G.M. (*n* = 13)					
SS ($m \cdot s^{-1}$)	1.10 ± 0.10 [a]	1.16 ± 0.12 [a]	1.22 ± 0.12 [a]	1.29 ± 0.13 [a]	1.36 ± 0.14 [a]
IdC_{adpt} (%)	-16.5 ± 4.5	-16.6 ± 5.9	-17.3 ± 5.6	-17.5 ± 5.3	-17.3 ± 5.2
IdC_{af} (%)	-24.0 ± 8.5	-24.1 ± 8.8	-23.8 ± 8.5	-24.1 ± 7.7	-24.3 ± 9.1
IdC_{un} (%)	-9.0 ± 9.8 [b]	-9.1 ± 10.4 [b]	-10.8 ± 9.5 [b]	-10.8 ± 8.8 [b]	-10.2 ± 8.7 [b]

[a] Significantly different with all SS_{max} values ($p < .01$).

[b] Differences between IdC_{af} and IdC_{un} are statistically significant ($p < .01$).

Between 80 and 100% of SS_{max} there was a significant increase in mean swimming speed (from 1.10 ± 0.10 $m \cdot s^{-1}$ to 1.36 ± 0.14 $m \cdot s^{-1}$; $p < .05$). Conversely, across the five percentage speed increments, there was no significant difference in mean IdC_{adapt} values. The mean IdC_{af} values (-24.1 ± 8.3%) were significantly lower ($p < .05$) than that of the mean IdC_{un} values (-10.0 ± 9.2%) at all percentage speed increments.

The mean values for both the IdC_{af} and IdC_{un} were not seen to change as the participants increased their swimming speed, between 80 and 100% of SS_{max}. At 80% of SS_{max}, the mean IdC_{af} value was -24.0 ± 8.5% and the mean IdC_{un} value was -9.0 ± 9.8%. At 100% of SS_{max}, the mean IdC_{af} value was -24.3 ± 9.1% and the mean IdC_{un} value was -10.2 ± 8.7%. There was no significant interaction effect on inter-arm coordination. Individual swimmer's IdC_{adapt} versus swimming speed curves can be found in Appendix IV.

Inter-swimmer correlation coefficients among swimming speed, stroke frequency, stroke length, adapted Index of Coordination and the relative durations of the arm stroke phases for both the affected- and unaffected-arms, at 100% of SS_{max}, are shown in Table 4.2.

At 100% of SS_{max}, correlation analysis showed that stroke frequency was significantly related to swimming speed ($r = .72$; $p < .05$) whereas stroke length was not ($r = .01$). Both swimming speed ($r = .59$) and stroke frequency ($r = .66$) were significantly related ($p < .05$) to IdC_{af}. There were moderate but non-significant correlations between swimming speed and IdC_{un} (r = -.30), and stroke frequency and IdC_{un} ($r = -.50$). Stroke frequency was significantly related ($p < .05$) to the relative stroke phase durations of the affected-arm (Entry and Glide: $r = -.74$; Pull: $r = .71$; Push: $r = .61$; Recovery: $r = -.71$), but not to the stroke phases of the unaffected-arm. IdC_{af} was also significantly related ($p < .05$) to the relative stroke phase durations of the affected-arm (Entry and Glide: $r = -.95$; Pull: $r = .75$; Push: $r = .71$; Recovery: $r = -.84$) and to the Push phase of the unaffected-arm ($r = .69$).

The fastest swimmers, who had the highest stroke frequencies, exhibited the least amount of catch-up of their affected-arm. Furthermore, the affected-arm of these swimmers spent the shortest percentage time in the Entry and Glide and Recovery phases and the longest percentage time in the Pull and Push phases.

Table 4.2. Inter-swimmer correlation coefficients among swimming speed, stroke frequency, stroke length, adapted index of coordination and relative arm stroke phase durations for both the affected- and unaffected-arms, at maximum swimming speed.

	Swimming speed ($m \cdot s^{-1}$)	Stroke frequency (Hz)	IdC_{af} (%)
Stroke frequency (Hz)	.72 [b]		
Stroke length (m)	.01	-.68 [a]	
IdC_{adpt} (%)	.26	.54	
Affected-arm			
IdC_{af} (%)	.59 [a]	.66 [a]	
Entry and Glide (%)	-.52	-.74 [b]	-.95 [b]
Pull (%)	.60 [a]	.71 [b]	.75 [b]
Push (%)	.31	.61 [a]	.71 [b]
Recovery (%)	-.50	-.71 [b]	-.84 [b]
Unaffected-arm			
IdC_{un} (%)	-.30	-.50	-.31
Entry and Glide (%)	.32 [c]	.39 [c]	.09 [c]
Pull (%)	-.35	-.29	-.37
Push (%)	.35 [c]	.40 [c]	.69 [b, c]
Recovery (%)	.29	.32	.54

[a] Correlations are statistically significant ($p < .05$).

[b] Correlations are statistically significant ($p < .01$).

[c] Correlations performed using Spearman Rank correlation tests

4.5 Discussion

The aim of this study was to examine the effect of swimming speed on inter-arm coordination and the inter-relationships between swimming speed, inter-arm coordination and other stroke parameters, in a group of competitive unilateral arm amputee front crawl swimmers. The first hypothesis was rejected: inter-arm coordination did not change as swimming speed was increased up to maximum. The second hypothesis was accepted: at sprint speed, higher inter-arm coordination indices were related to stroke frequency and swimming speed. The fastest swimmers used higher stroke frequencies and less catch-up of their affected-arm, than the slower swimmers.

The mean IdC_{adapt} value of the amputees did not change with an increase in swimming speed up to maximum. At all swimming speeds, arm coordination conformed to that of catch-up. There was significantly more catch-up (i.e. time delay) of the amputees' affected-arm (IdC_{af}) than that of their unaffected-arm (IdC_{un}), at all swimming speeds. This asymmetrical catch-up did not appear to be affected by an increase in swimming speed, suggesting that swimmers maintained stable inter-arm coordination even though they swam faster. These findings contrast with those found for able-bodied front crawl swimmers. Chollet et al. (2000), Potdevin et al. (2006) and Seifert et al. (2004) all reported that able-bodied swimmers modified their arm coordination with increases in swimming speed. Swimmers switched from using catch-up at slow swimming speeds (-6.9 ± 7.1 %, Chollet et al., 2000; -11.9 ± 3.0 %, Potdevin et al., 2006; -10.5 ± 5.3 %, Seifert et al., 2004), to opposition or superposition at fast swimming speeds (2.5 ± 4.4 %, Chollet et al., 2000; 0.3 ± 2.0 %, Potdevin et al., 2006; 2.6 ± 6.1 %, Seifert et al., 2004). Such changes coincided with increases in stroke frequency.

Although the mean IdC_{adapt} value did not change with an increase in speed, all the arm amputee swimmers in this study were able to progressively increase their swimming speed by increasing their stroke frequency. The increase in stroke frequency coincided with a decrease in stroke length. As the swimmers in this study were the same as those in the study by Osborough et al. (2009), their stroke frequency and stroke length values are presented in Table 3.1. Between 80 and 100% of SS_{max}, mean stroke frequency increased (from 0.57 ± 0.18 Hz to 0.82 ± 0.11 Hz) and mean stroke length decreased (from 1.78 ± 0.15 m to 1.66 ± 0.16 m) with an increase in mean swimming speed(from 1.10 ± 1.10 $m \cdot s^{-1}$ to 1.36 ± 0.14 $m \cdot s^{-1}$). Thus unlike able-bodied swimmers, the amputees kept the time lag between the end of the Push of one arm and the beginning of the Pull of the other relatively constant, even though they increased the rate of rotation of their arms.

The observed arm coordination differences between the amputee swimmers in this study and those in the Chollet et al. (2000), Potdevin et al. (2006) and Seifert et al. (2004) studies could be accounted for by the way in which arm coordination was quantified and by the difference between the two populations. In the current study the IdC_{adapt} was used. It was anticipated that this index would over-estimate the time delay between the beginning of the Pull phase of one arm and the end of the Push phase of the other, in comparison to the original IdC as defined by Chollet et al. (2000). Even with this difference, changes in arm coordination with increases in swimming speed were still expected. Due to their physical impairment, the amputee swimmers were considerably slower than those in the Chollet et al. (2000), Potdevin et al. (2006) and Seifert et al. (2004) studies. Hence, the amputees would have experienced less resistive force when swimming. As the amputees were unable to attain a speed of 1.8 $m \cdot s^{-1}$, they did not reach the critical point where able-bodied swimmers have been observed to switch their arm coordination to overcome the large resistive forces that occur when swimming around this speed (e.g., Chollet et al., 2000; Seifert et al., 2004; Seifert et al., 2007). This might explain why the rhythmical, intrinsic anti-phase inter-limb relationship of the unilateral arm amputee front crawl swimmers was strongly preserved, despite a change in the task constraint.

The asymmetrical nature of the amputees' inter-arm coordination has also been observed, to a lesser extent, in able-bodied front crawl swimmers (Seifert et al., 2005). In these swimmers, coordination asymmetry has been related to the preferential breathing side and the dominant arm. In the current study, the effect of the breathing action on the swimming stroke was controlled. Therefore, the asymmetrical inter-arm coordination of the amputee swimmers might relate to the different roles that the affected- and unaffected-arm may have within the front crawl arm stroke cycle. It would be expected that the primary function of the unaffected-arm is to generate propulsion. Conversely, the affected-arm might simply function to control inter-arm asymmetry, so that stable repetition of the overall arm stroke cycle is maintained, rather than contribute effectively to propulsion.

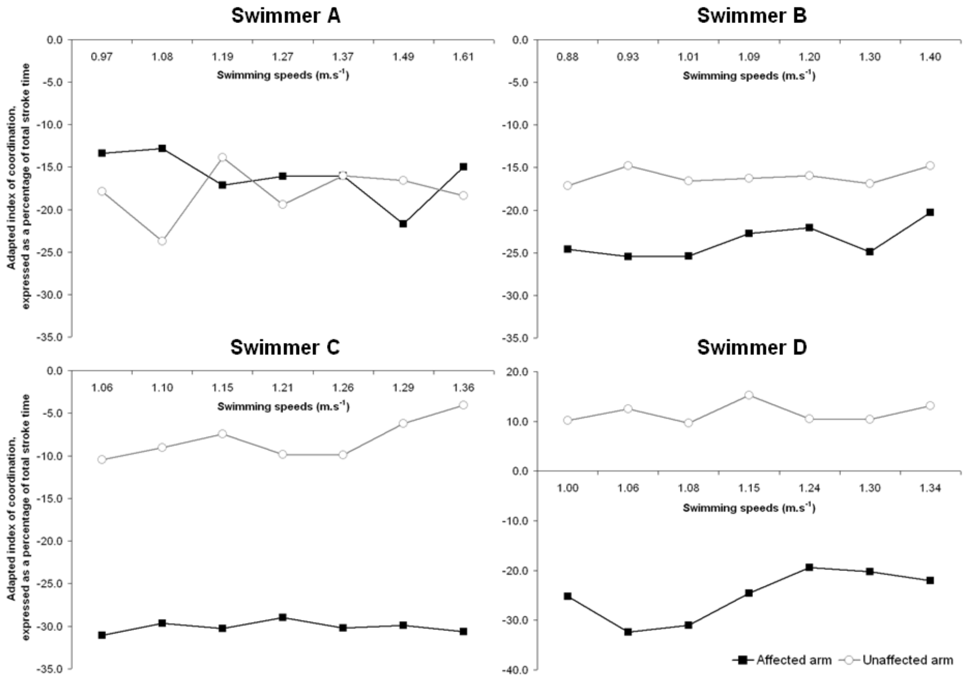

Figure 4.3. Individual examples of four different inter-arm coordination styles exhibited within the group of unilateral arm amputee front crawl swimmers.

Within the current group of swimmers, different amounts of coordination asymmetry were evident between the affected- and unaffected-arm strokes. Four examples of different inter-arm coordination styles are shown in Figure 4.3: (1) where the affected- and unaffected-arms showed near-symmetrical catch-up (i.e. both arms had similar IdC_{adapt} values, e.g., Swimmer A, who was the fastest male swimmer); (2) where slightly more catch-up was exhibited by the affected-arm (i.e. the IdC_{af} was more negative than the IdC_{un}, e.g., Swimmer B, who was the fastest female swimmer); (3) where there was a large difference between the catch-up of the affected-arm and that of the unaffected-arm (i.e. the IdC_{af} was much more negative than the IdC_{un}, e.g., Swimmer C, who was a mid-level female swimmer); (4) where the unaffected-arm exhibited superposition and the affected-arm exhibited catch-up (e.g., Swimmer D, who was a mid-level female swimmer).

The existence of different inter-arm coordination styles indicated that different compensatory motor strategies had developed within the group of amputee swimmers, as a consequence of their physical impairment. These strategies appeared to be: (1) as one arm was close to exiting the water, the other was close to entering the water (e.g., Swimmers A and B); (2) the affected-arm was held stationary in front of the body as the unaffected-arm was pushed rapidly towards the hip into the Recovery phase, after which time the affected-arm was pulled rapidly under the shoulder (e.g., Swimmer C); (3) as the unaffected-arm recovered, the affected-arm was moved steadily through the underwater phases before being held stationary by the side of the body until such time as the unaffected-arm had commenced its Pull phase (e.g., Swimmer D). However, as propulsion was not quantified in this study, it is unclear whether some of these motor strategies resulted in more effective stroking technique, than others.

In the current study the nature of the leg kick in relation to the arm stroke was not examined. In able-bodied front crawl, the leg kick is thought to be responsible for about 10% of the total propulsion (Deschodt et al., 1999). It is also believed that the leg kick helps to counteract the rolling action of the trunk (Yanai, 2003) and reduce the resistive forces a swimmer may experience. It would be reasonable to assume that the asymmetrical inter-arm coordination observed in this study would have influenced the nature of the amputees' leg kick. This has important implications for how these swimmers reduce resistance effectively when swimming and how they stabilise the rolling action of their trunk. Understanding the inter-relationships between inter-limb coordination and swimming performance would be of great practical importance to swimmers and coaches and warrants further study.

The inter-swimmer correlations in this study showed that there were significant relationships between SS_{max} and the stroke frequency and the IdC_{af} used at SS_{max}. The fastest amputee swimmers used higher stroke frequencies and less catch-up of the affected-arm, when compared to the slower swimmers. Satkunskiene et al. (2005) reported that "more-skilled" swimmers, with various loco-motor disabilities, were characterised by greater amounts of superposition and higher stroke frequencies, when compared to "less-skilled" swimmers. Other authors have also shown that stroke frequency significantly correlates with arm coordination (r = .67, Chollet et al., 2000; r = .76, Seifert et al., 2004). The findings from this study imply that when sprinting, the attainment of a high stroke frequency is mainly influenced by the catch-up style of the affected-arm. Reducing the time delay before initiating the affected-arm pull appears to be a beneficial strategy which allows for attainment of the highest stroke frequencies and swimming speeds.

At SS_{max}, there were significant correlations between stroke frequency and the IdC_{af} and the relative durations of the arm stroke phases of the affected-arm. The fastest amputee's affected-arm spent less time in the Entry and Glide and Recovery phases and more time in the Pull and Push phases, when compared to the slower swimmers. For able-bodied swimmers (Chollet et al., 2000) and swimmers with a loco-motor disability (Satkunskiene et al., 2005) higher IdC values and higher stroke frequencies were significantly related to shorter Entry and Glide phase durations and longer Pull phase durations. In this regard, the faster amputees in this study exhibited similar characteristics to those of other swimmers, when compared to their slower counterparts. This implies that the catch-up style of the affected-arm is mainly influenced by the duration of the Entry and Glide phase of the same arm.

4.6 Summary and Conclusion

The results from this study show that the inter-arm coordination of the amputees did not change with an increase in swimming speed up to maximum. Swimmers showed significantly more catch-up of their affected-arm compared to their unaffected-arm. When sprinting, the fastest swimmers used higher stroke frequencies and less catch-up of their affected-arm, when compared to the slower swimmers. These findings imply that: (1) unilateral arm amputee front crawl swimmers use a strategy for asymmetrical coordinating their affected-arm relative to their unaffected-arm in order to maintain the stable repetition of their overall arm stroke cycle; and (2) when sprinting, the attainment of a high stroke frequency is influenced mainly by the catch-up style of the affected-arm. For these swimmers, reducing the time delay (i.e. the Entry and Glide phase duration) before initiating the affected-arm pull appears to be a beneficial strategy, which allows for the attainment of the highest stroke frequencies and swimming speeds.

CHAPTER FIVE

EFFECT OF SWIMMING SPEED ON LEG KICK AND ARM STROKE COORDINATION

This chapter describes the coordination of the leg kick in relation to the arm stroke cycle. The chapter establishes whether the coordination of the leg kick mirrored the asymmetrical coordination of the arm stroke and examines whether leg-to-arm coordination changed at different swimming speeds. The spatio-temporal nature of leg-to-arm coordination is also discussed. Chapter 5 relates to academic aim 3, in Section 2.13.

5.1 Abstract

The aim of this study was to examine the effect of swimming speed on leg kick and arm stroke coordination, in a group of competitive unilateral arm amputee front crawl swimmers. Thirteen highly-trained swimmers were filmed underwater during three 25 m front crawl trials performed at 400 m, 100 m and 50 m pace. Increases in swimming speed corresponded with increases in stroke and kick frequency. With increasing speed, swimmers did not change the number of kicks they performed per arm stroke cycle. When sprinting, swimmers predominantly used a six-beat leg kick (n = 10), although four-beat (n = 2) and eight-beat leg kicks (n = 1) were also used. There was significant temporal asymmetry between the swimmers' affect- and unaffected-arm stroke phases. In contrast, the kicking phases between legs were symmetrical. Inter-arm and inter-leg coordination did not change with an increase in swimming speed. Swimmers displayed asymmetrical leg-to-arm coordination between both sides of the body, as a consequence of asymmetrical inter-arm coordination and symmetrical inter-leg coordination. By rhythmically aligning their leg kicks with particular arm stroke phases, unilateral arm amputee front crawl swimmers might enhance performance and maintain the stable repetition of their overall arm stroke cycle.

5.2 Introduction

In front crawl, the leg kick aids the generation of propulsion (Bucher, 1975; Hollander et al., 1988; Sanders & Psycharakis, 2009), helps to streamline the body (Counsilman, 1971) and acts to stabilise the rolling action of the trunk (Counsilman, 1968; Yanai, 2003). Propulsion may be generated directly from the leg kick, by a swimmer sequencing the undulations of their lower extremity segments to induce a wave that travels caudally from hip to ankle with increasing amplitude and velocity (Sanders, 2007[b]; Sanders & Psycharakis, 2009). The leg kick may also contribute to propulsion indirectly, by a swimmer organising leg-to-arm coordination to facilitate an advantageous underwater arm trajectory, which might produce a more effective arm stroke action compared to that when swimming arms only (Deschodt et al., 1999; Watkins & Gordon, 1983). Kicking the legs whilst swimming, helps to raise them high in the water allowing a swimmer to maintain a horizontal body position, thus reducing the resistance experienced and improving swimming economy (Chatard et al., 1990). The kicking action is also speculated to contribute to the torque generated about the swimmer's long-axis during the swimming stroke, which acts to stabilise trunk roll (Eaves, 1971; Yanai, 2003). The function of the leg kick therefore is multi-facetted and complex, particularly when the coordination between the arm stroke and leg kick components is considered during front crawl swimming.

The most commonly reported kicking action in able-bodied front crawl consists of three upbeats and three downbeats of each leg per arm stroke cycle and is often referred to as a six-beat kick (Sanders & Psycharakis, 2009; Yanai, 2003). However, authors have reported that able-bodied swimmers (Chollet et al., 2000; Persyn et al., 1983) and triathletes (Hue, Benavente, & Chollet, 2003; Millet et al., 2002) also use four-beat and two-beat kicks when swimming front crawl at different speeds. In competition, it is likely that swimmers elect to use a six-, four- or two-beat kick to optimise their performance depending on: (1) the specific event distance being swum; (2) their physical characteristics; and (3) their preferred leg-to-arm coordination pattern learnt during training (Persyn et al., 1983).

In able-bodied front crawl, the leg kicks are rhythmically executed within the arm stroke cycle, such that the downbeats of the kick clearly coincide with particular phases during the arm stroke (Eaves, 1971; Maglischo, 2003; Persyn et al., 1983; Yanai, 2003). With a two-beat kick, the downbeat of the left leg occurs near the beginning of the right arm's underwater pull. This would be mirrored near the beginning of the left arm's underwater pull. With a six-beat kick, the first downbeat of the left leg coincides with the Entry and Glide phase of the right arm, the following downbeat of the right leg is executed during the Downsweep phase of the right arm and the second downbeat of the left leg occurs as the right arm completes the Insweep phase. This is then repeated on the other side of the body. Such leg-to-arm coordination suggests that able-bodied front crawl swimmers align their leg kick with their arm stroke to enhance performance, rather than kicking their legs independently of moving their arms. A swimmer's ability to integrate the timing of their leg kick effectively into the arm stroke cycle is important for fast swimming, more so than being able to attain a high speed when just kicking. By rhythmically aligning their leg kicks with particular arm stroke phases, able-bodied swimmers might also be able to maintain stable inter-arm coordination throughout the duration of a race (Seifert, Boulesteix, Carter, & Chollet, 2004).

Inter-arm coordination for competitive front crawl swimmers with a single, elbow-level amputation has been shown to be asymmetrical and stable over a range of swimming speeds (Osborough, Payton, & Daly, 2010). However in their study, these authors did not examine the coordination between the keg kick and the arm stroke. Given the clear leg-to-arm coordination in able-bodied front crawl, it seems probable that the asymmetrical nature of the amputees' inter-arm coordination might influence their inter-leg coordination. An examination into how unilateral arm amputees coordinate their leg kick with their asymmetrical arm stroke is warranted. With asymmetrical inter-arm coordination, it could be speculated that single-arm amputees might exhibit: (1) asymmetrical inter-leg coordination that results in leg-to-arm coordination being the same on both sides of the body; or (2) symmetrical inter-leg coordination that results in leg-to-arm coordination being different on both sides of the body.

The aim of this study was to examine the effect of swimming speed on leg kick and arm stroke coordination, in a group of competitive unilateral arm amputee front crawl swimmers. Since unilateral arm amputee front crawl swimmers do not change their inter-arm coordination with increases in swimming speed and for these swimmers, their leg kick is probably aligned with their arm stroke, it would be expected that changes in swimming speed would not influence leg-to-arm coordination. The hypothesis for this study was that the leg kick and arm stroke coordination would not change with an increase in swimming speed.

5.3 Methods

5.3.1 Participants

Thirteen (3 male and 10 female) competitive swimmers (age 16.9 ± 3.1 yrs; height 1.69 ± 0.09 m; mass 63.6 ± 13.0 kg), whose mean long course 50 m front crawl personal best time was 32.7 ± 3.1 seconds, participated in this study. All the participants were single-arm amputees, at the level of the elbow and were the same as those who participated in Study 1 and Study 2 (Chapters 3 and 4). Further details of the participant group can be found in Section 3.3.1. The procedure for the data collection was approved by the Institutional Ethics Committee. All participants provided either written informed consent or, in the case of minors, parental written consent before taking part in the study.

5.3.2 Data Collection

After a standardised 600 m warm up each participant completed three self-paced 25 m front crawl trials, from a push start, at intervals of 3 minutes. Participants were requested to swim each trial at a predetermined target pace, based on their 400 m, 100 m and 50 m front crawl personal best times; these being the events held at the Paralympic Games. Seven of the swimmers performed the trials from 400 m pace to 50 m pace; the others performed the trials from 50 m pace to 400 m pace. All trials were manually recorded by two experienced timekeepers using chronograph stopwatches (Model 898). Any trial that was not within ± 2% of the target pace was repeated after a 3 minute rest. To control for the effects of the breathing action on the swimming stroke, participants were instructed not to take a breath through a 10 m test section of the 25 m pool.

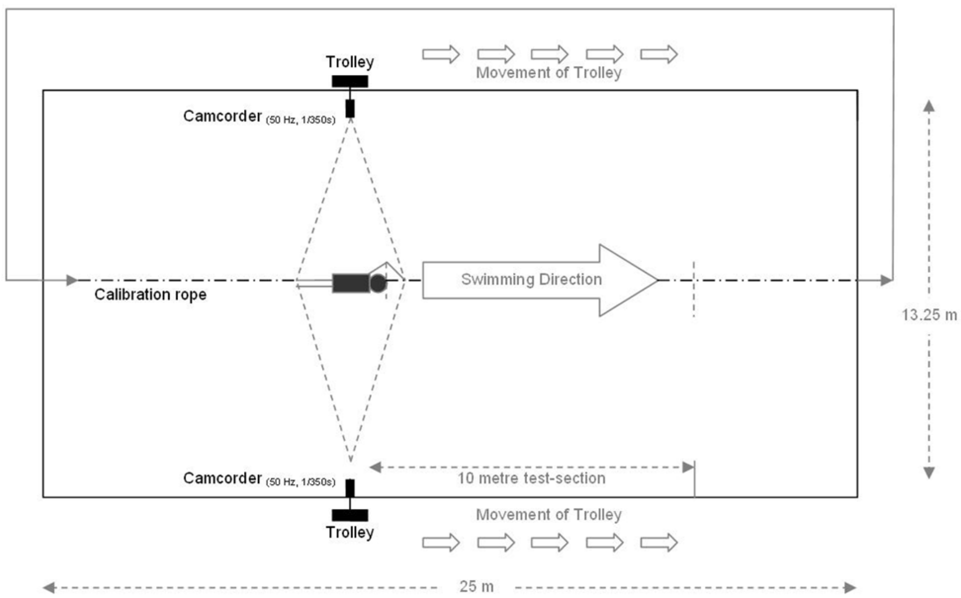

Figure 5.1. Plan view of the two-dimensional filming set-up.

Two digital video camcorders (Panasonic NVDS33), sampling at 50 Hz with a shutter speed of 1/350 s, were used to film the participants under the water, from opposite sides of the pool (Figure 5.1). Each camcorder was enclosed in a waterproof housing suspended underwater from a trolley that ran along the side of the pool, parallel to the participants' swimming direction. The field of view of each camcorder was adjusted so that the whole body of each participant was visible. To scale the recorded video footage and account for camcorder movement, a calibration rope, with markers every metre, was suspended horizontally in the water directly beneath the participant. Operators pulled the trolleys at the same speed as the participants, keeping the participant's hip joint marker in the centre of the field of view.

5.3.3 Data Processing

The digital video footage was transferred to a laptop computer and analysed using SIMI Motion 7.2 software (SIMI Reality Motion Systems GmbH, Unterschleißheim, Germany). Three consecutive, non-breathing stroke cycles for each participant were selected for analysis. A stroke cycle was defined as the period from water entry of the hand of the unaffected-arm, to the next entry of that hand. The estimated locations of the gleno-humeral joint centre and the elbow joint centre of both the affected- and unaffected-arms were digitised at 50 Hz to obtain the angular position of the upper-arms, as a function of time. Upper-arm angle was defined as the angle between the upper-arm and a horizontal reference, established using the water surface. To obtain the vertical displacement of the feet during the kick, the estimated locations of the ankle joint centre and the tip of the foot were digitised at 50 Hz. The midpoint of the line intersecting these two landmarks was used to determine the position of each foot, as a function of time. Before filming, the skin overlaying the joint centres was marked with black pen to help estimate their location.

5.3.4 Definition of Variables

The stroke cycle of each arm and the kick cycle of each leg were divided into two phases:

Arm Cycle Phase 1: *Pull*: from where the elbow joint centre entered the water (0°) to where the shoulder-to-elbow position vector made an angle of 155° with the horizontal.

Arm Cycle Phase 2: *Recovery*: from the end of the Pull (155°) to where the elbow joint centre re-entered the water (360°).

Kick Cycle Phase 1: *Upbeat*: from where the foot was at its deepest point in the water to where it was at its highest point.

Kick Cycle Phase 2: *Downbeat*: from the end of the upbeat to where the foot was again at its deepest point. A leg kick was thus defined as the upbeat and downbeat of a single leg.

The following variables were then calculated, as a mean of three stroke cycles, at each participant's 400 m, 100 m and 50 m front crawl swimming pace: 1) *Swimming speed* ($m \cdot s^{-1}$): mean forward speed of the participant; 2) *Stroke frequency* (Hz): number of stroke cycles performed in one second; 3) *Kick frequency* (Hz): number of kick cycles performed in one second; 4) *Pull time* (%): time taken for each arm to complete the underwater Pull phase of the stroke, expressed as a percentage of the complete arm stroke cycle duration; 5) *Recovery time* (%): time taken for each arm to complete the above water Recovery phase of the stroke, expressed as a percentage of the complete arm stroke cycle duration; 6) *Upbeat time* (%): mean time taken for each leg to complete the upbeat phases of the kick, expressed as a percentage of the complete leg kick cycle duration; 7) *Downbeat time* (%): mean time taken for each leg to complete the downbeat phases of the kick, expressed as a percentage of the complete leg kick cycle duration; 8) *Leg-to-arm frequency coordination*: number of observed leg kicks per arm stroke cycle; 9) *Leg-to-arm spatial coordination* (°): angular position of each upper-arm at the instant when: (1) the first opposite-side leg downbeat ($DB1_{opp}$) ended; (2) the first same-side leg downbeat ($DB1_{same}$) ended; (3) the second opposite-side leg downbeat ($DB2_{opp}$) ended; and (4) the second same-side leg downbeat ($DB2_{same}$) ended.

5.3.5 Statistical Analyses

Means and standard deviations were computed for all the measured variables. Normal distribution of the data was verified using the Shapiro-Wilks test. Three separate univariate general linear modeling (GLM) tests were used to compare changes in swimming speed, stroke frequency and kick frequency between the 400 m, 100 m and 50 m paces. Sphericity was assessed by means of the Mauchley test and adjusted via the Greenhouse-Geisser procedure. Multiple comparisons were made with the Bonferroni *post hoc* test. Four separate multifactorial repeated measures GLM tests were used to compare pull time, recovery time, upbeat time and downbeat time between swimming paces and between contra-lateral limbs. A chi-square (χ^2) test was used to compare the number of swimmers who used different leg-to-arm frequency coordination at the 400 m, 100 m and 50 m paces. For those participants who used a six-beat kick, three separate multifactorial repeated measures GLM tests were used to compare leg-to-arm spatial coordination between swimming paces and between contra-lateral limbs. In all comparisons, the level of significance was set at $p < .05$. Statistical analysis procedures were performed using SPSS 16.0 software.

5.4 Results

Between the 400 m and the 50 m swimming pace trial (Table 5.1), mean swimming speed significantly increased (from 1.15 ± 0.12 $m \cdot s^{-1}$ to 1.36 ± 0.14 $m \cdot s^{-1}$; $p < .01$), as did mean stroke frequency (from 0.65 ± 0.08 Hz to 0.82 ± 0.11 Hz; $p < .01$) and mean kick frequency (from 1.86 ± 0.31 Hz to 2.38 ± 0.32 Hz; $p < .01$).

Table 5.1. Means (M) and standard deviations (SD) of swimming speed, stroke frequency and kick frequency for front crawl swimmers at 400 m (84 ± 0.9% of SS_{max}), 100 m (94 ± 1.3% of SS_{max}) and 50 m (SS_{max}) pace (male: ♂, female: ♀, group mean: G.M.).

Gender	**Swimming Pace**	**Swimming speed ($m \cdot s^{-1}$)**		**Stroke Frequency (Hz)**		**Kick Frequency (Hz)**	
		M	***SD***	***M***	***SD***	***M***	***SD***
♂ (*n* = 3)	50 m	1.47	.09	0.88	.07	2.32	.37
♀ (*n* = 10)	50 m	1.33	.13	0.81	.12	2.40	.33
G.M. (n = 13)	50 m	1.36	.14 [a]	0.82	.11 [a]	2.38	.32 [a]
♂ (*n* = 3)	100 m	1.39	.07	0.81	.08	2.14	.30
♀ (*n* = 10)	100 m	1.22	.13	0.71	.09	2.07	.37
G.M. (n = 13)	100 m	1.26	.14 [a]	0.74	.09 [a]	2.08	.35 [a]
♂ (*n* = 3)	400 m	1.24	.07	0.70	.06	1.84	.25
♀ (*n* = 10)	400 m	1.13	.12	0.64	.08	1.86	.33
G.M. (n = 13)	400 m	1.15	.12 [a]	0.65	.08 [a]	1.86	.31 [a]

[a] Differences between swimming paces were statistically significant ($p < .01$).

The mean relative pull and recovery times of the affected- and unaffected-arm are shown in Table 5.2. Also shown are the mean relative upbeat and downbeat times of both legs, on the affected- and unaffected-side of the swimmer.

At all swimming paces, there was significant temporal asymmetry between the phases of the affected- and the unaffected-arm. The mean relative pull time of the affected-arm (69 ± 5%) was significantly longer ($p < .01$) than that of the unaffected-arm (63 ± 4%). Consequently, the mean relative recovery time of the affected-arm (31 ± 5%) was significantly shorter ($p < .01$) than that of the unaffected-arm (37 ± 4%). The magnitude of temporal asymmetry remained similar across the three swimming paces.

Table 5.2. Means (M) and standard deviations (SD) of relative arm stroke and leg kick phase durations on the unaffected- and affected-side of the front crawl swimmers at 400 m, 100 m and 50 m pace.

Limb	Swimming Pace	Pull Time (%)		Recovery Time (%)		Upbeat Time (%)		Downbeat Time (%)	
		M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Unaffected-side	50 m	62	2 [a]	38	2 [a]	53	3	47	3
	100 m	62	7 [a]	38	7 [a]	54	8	46	7
	400 m	64	3 [a]	36	3 [a]	52	4	48	4
Affected-side	50 m	68	5 [a]	32	5 [a]	52	2	48	2
	100 m	69	5 [a]	31	5 [a]	55	10	45	5
	400 m	71	5 [a]	29	5 [a]	53	5	47	5

[a] Denotes significant differences (p < .01) between affected- and unaffected-sides, for a given swimming pace.

In comparison to the arm stroke phases, the duration of the leg kick phases on the affected- and unaffected-side were very similar, at all swimming paces. Mean relative upbeat time, averaged across the three paces, on the affected-side of the swimmer was the same as that on the unaffected-side (53 ± 6% vs. 53 ± 5%, respectively). The mean relative downbeat time, averaged across the three paces, was 47 ± 4% compared to 48 ± 5% on the unaffected-side. The temporal symmetry of the leg kick action did not change as the participants increased their swimming speed from 400 m to 50 m pace.

Within the group, swimmers used different leg-to-arm frequency coordination strategies (Table 5.3). At 400 m pace and 100 m pace, nine swimmers used a six-beat kick, three used a four-beat kick and one used an eight-beat kick. At 50 m pace, only one swimmer switched her leg-to-arm frequency coordination from a four-beat kick to a six-beat kick. As a group, swimmers did not change the number of leg kicks they performed per arm stroke cycle when they increased their swimming speed. Swimmers maintained stable leg-to-arm frequency coordination across the different swimming paces.

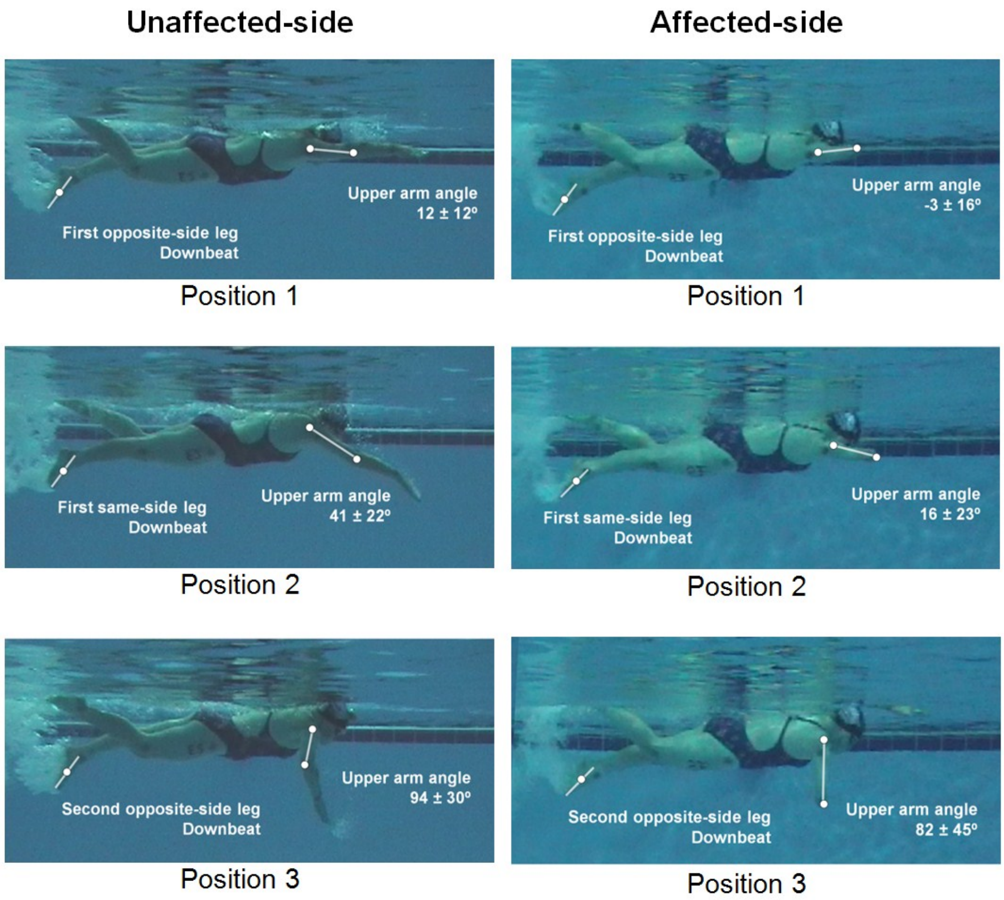

Figure 5.2. Front crawl leg-to-arm spatial coordination, on the unaffected- and affected-side of swimmers using a six-beat kick, at 100 m pace.

Table 5.3. Means (M) and standard deviations (SD) of leg-to-arm frequency and spatial coordination on the unaffected- and affected-side of the front crawl swimmers at 400 m, 100 m and 50 m pace.

Frequency Coordination	Swimming Pace	Angular position (°) of the Affected-arm when downbeat ends on the same and opposite sides							Angular position (°) of the Unaffected-arm when downbeat ends on the same and opposite sides						
		$DB1_{opp}$		$DB1_{same}$		$DB2_{opp}$		$DB2_{same}$	$DB1_{opp}$		$DB1_{same}$		$DB2_{opp}$		$DB2_{same}$
		M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*
8-beat kick															
(*n* = 1)	50 m	0		4		5		97	1		9		28		69
(*n* = 1)	100 m	-1		2		4		96	-3		8		20		68
(*n* = 1)	400 m	-2		6		9		99	1		9		22		65
6-beat kick															
(*n* = 10)	50 m	-3	16[a]	17	23[a]	82	44		13	18[a]	37	25[a]	96	28	
(*n* = 9)	100 m	-3	16[a]	16	23[a]	82	45		12	12[a]	41	22[a]	94	30	
(*n* = 9)	400 m	-1	15[a]	14	26[a]	79	44		13	12[a]	41	22[a]	90	36	
4-beat kick															
(*n* = 2)	50 m	55	8	114	11				13	17	41	13			
(*n* = 3)	100 m	80	19	152	7				8	13	35	5			
(*n* = 3)	400 m	95	19	155	8				11	12	40	1			

[a] Denotes significant differences ($p < .05$) between affected- and unaffected-side, for a given swimming pace.

All participants exhibited asymmetrical leg-to-arm spatial coordination between their affected- and unaffected-side, at all swimming speeds (Table 5.3). For those who used a six-beat leg kick (Figure 5.2) the mean angular position of the unaffected-arm was 13 ± 14°, 40 ± 23° and 93 ± 31° at the end of the first (opposite-side), second (same-side) and third (opposite-side) downbeat, respectively. In comparison, the mean unaffected-arm angle was -2 ± 16°, 16 ± 24° and 81 ± 44° at the same instances. For those who used four-beat leg-to-arm frequency coordination the mean affected-arm angle was 11 ± 14° and 39 ± 6° at the end of the first (opposite-side) and second (same-side) downbeat, respectively, while the mean unaffected-arm angle was 77 ± 15° and 140 ± 6° at the same instances. Inter-limb asymmetry was also evident for the single participant who used eight-beat leg-to-arm frequency coordination. For the participants who used a six-beat leg kick, no change in leg-to-arm spatial coordination was observed as they increased their swimming speed from 400 m to 50 m pace.

5.5 Discussion

The aim of this study was to examine the effect of swimming speed on leg kick and arm stroke coordination, in a group of competitive unilateral arm amputee front crawl swimmers. The hypothesis for this study was accepted. The leg kick and arm stroke coordination did not change with an increase in swimming speed.

As the arm amputees increased their swimming speed from 400 m to 50 m pace their stroke frequency and kick frequency significantly increased. Changes in mean stroke frequency (from 0.65 to 0.82 Hz) were comparable to those reported by Chollet et al. (2000) for fourteen high performing able-bodied swimmers (from 0.60 to 0.90 Hz), by Hue et al. (2003) for twelve national and international triathletes (from 0.60 to 0.86 Hz) and by Osborough et al. (2009) for thirteen single-arm amputee swimmers (from 0.58 to 0.82 Hz). In this study, mean kick frequency (1.86 Hz) at the 400 m swimming pace was similar to that reported by Fulton et al. (2009) for two arm amputee swimmers (one S9 Class; one S8 Class) during a 100 m front crawl time-trial (1.87 Hz).

At all paces, the relative duration of the Pull and Recovery phases significantly differed between the affected- and unaffected-arm. These phase durations remained similar despite an increase in swimming speed. At all swimming speeds, the time that the amputees spent pulling their affected-arm through the water was relatively longer than that of their unaffected-arm, while the relative duration of the amputee's affected-arm Recovery was shorter than that of their unaffected-arm. These findings are similar to those of Osborough et al. (2010) and show that the swimmers exhibited asymmetrical inter-arm coordination which remained stable at different swimming speeds.

The asymmetrical nature of the amputees' inter-arm coordination did not appear to influence inter-leg coordination. In contrast to the phases of the affected- and unaffected-arm stroke, the kicking phases between legs were temporally symmetrical. The relative durations of the amputees' upbeat and downbeat on their affected- and unaffected-side were similar and did not change with an increase in swimming speed. Inter-leg coordination was both symmetrical and stable. The unilateral arm amputee front crawl swimmers executed their leg kicks rhythmical, within the overall duration of the arm stroke cycle.

Within the current group of swimmers different patterns of leg-to-arm frequency coordination were evident. Three main kicking actions are reported in the literature for able-bodied swimmers. These are two-, four- and six-beat kicks (Persyn et al., 1983). In sprint events the most commonly used is the six-beat kick, characterised by continuous kicking, while in long-distance events the two- and four-beat kick are most frequently used. In the present study 69.2% (n = 9) of the swimmers used a six-beat kick, 23.1% (n = 3) used a four-beat kick and 7.7% (n = 1) unexpectedly used an eight-beat kick to swim at their 400 m pace and 100 m pace. At 50 m pace only one swimmer switched her leg-to-arm frequency coordination from a four- to a six-beat kick. At this pace 76.9% (*n* = 10) of the swimmers used a six-beat kick, 15.4% (*n* = 2) used a four-beat kick and 7.7% (*n* = 1) used an eight-beat kick.

An eight-beat kick in front crawl swimming has not been previously reported. This characteristic demonstrates that, as a consequence of her physical impairment, the swimmer who used an eight-beat kick functionally adapted her motor organisation to swim front crawl. Interestingly, this swimmer was the slowest swimmer in the group and also exhibited the slowest stroke frequency at each swimming pace (at 400 m pace: 0.95 $m \cdot s^{-1}$ and 0.48 Hz; at 100 m pace: 1.02 $m \cdot s^{-1}$ and 0.53 Hz; at 50 m pace: 1.13 $m \cdot s^{-1}$ and 0.60 Hz). It is likely that the swimmer used a relatively low stroke frequency, for a given swimming speed, so that she was able to execute the eight kicks within the stroke cycle.

As a group, leg-to-arm frequency coordination did not significantly change with an increase in swimming speed. These findings contrast with those found for able-bodied triathletes and front crawl swimmers. Chollet et al. (2000), Hue et al. (2003) and Millet et al. (2002) all reported that the proportion of swimmers and triathletes using a six-beat kick significantly increased with an increase in swimming speed. Chollet et al. (2000) reported that 58% of swimmers swam using a six-beat kick at 800 m pace with this increasing to 91% at 50 m pace. Similarly, Millet et al. (2002) showed that 86.7% of swimmers and 63% of triathletes used a six-beat kick at 800 m pace, while at 50 m pace 93.3% of swimmers and 84% of triathletes used a six-beat kick. In the study by Hue et al. (2003), 50% of triathletes swam using a six-beat kick at 800 m pace with this increasing to 75% at 50 m pace. Since the amputees' leg-to-arm frequency coordination did not change, it could be argued that these swimmers elected to use a six-, four- or eight-beat kick as a consequence of their physical characteristics and preferred leg-to-arm coordination pattern, rather than as a result of the specific pace being swum.

The amputee swimmers who used a six-beat kick did not significantly change their leg-to-arm spatial coordination with an increase in swimming speed. For these swimmers, leg-to-arm spatial coordination significantly differed between the affected- and unaffected-side. For their unaffected-arm, at 100 m pace, the end of the first downbeat on the opposite side coincided with the Entry and Glide phase (upper-arm angle = 12°), the following downbeat of the same-side leg was executed during the Downsweep phase (upper-arm angle = 41°) and the second downbeat of the opposite-side leg occurred as the unaffected-arm completed its Insweep phase (upper-arm angle = 94°). This leg-to-arm coordination suggests that the unilateral arm amputee swimmers aligned their leg kick with their unaffected-arm as able-bodied front crawl swimmers do for both arms (Maglischo, 2003; Persyn et al., 1983; Yanai, 2003). In contrast, for the affected-arm of the amputees, the end of the first downbeat on the opposite side coincided with the Entry and Glide phase (upper-arm angle = -3°), as did the following downbeat of the same-side leg (upper-arm angle = 16°). The second downbeat of the opposite-side leg occurred as the unaffected-arm was being brought underneath the shoulder (upper-arm angle = 82°). Using this leg-to-arm coordination, the arm amputees executed two leg kicks before pulling their affected-arm through the water. The unilateral arm amputee front crawl swimmers displayed leg-to-arm coordination that was different on both sides of the body as a consequence of asymmetrical inter-arm coordination and symmetrical inter-leg coordination. Being able to dissociate their leg kick and arm stroke demonstrates that, as a consequence of their physical impairment, unilateral arm-amputee swimmers functionally adapted their motor organisation to swim front crawl. By using asymmetrical leg-to-arm coordination it is likely that these swimmers coordinated their leg kick with their arm stroke to enhance performance, rather than kicking their legs independently of moving their arms.

With asymmetrical leg-to-arm coordination, the leg kick might have served a variety of different functions during the arm amputees' front crawl stroke. For example, as the amputees' leg kick clearly coincided with particular phases during the unaffected-arm stroke, these being similar to those described for able-bodied swimmers, the amputees may have organised their leg-to-arm coordination to facilitate an advantageous underwater arm trajectory. This might have produced a more effective arm stroke action compared to that when swimming arms only (Deschodt et al., 1999). Furthermore, the amputees executed two kicks while the affected-arm was held stationary in front of the body as the unaffected-arm was recovered over the water. Since the propulsive effect of the arm action was interrupted at this point in the stroke cycle, it is likely that the leg kicks ensured ongoing propulsion (Sanders & Psycharakis, 2009). Finally, by rhythmically aligning their leg kicks with particular arm stroke phases, the unilateral arm amputee front crawl swimmers might have maintained the stable repetition of their overall arm stroke cycle (Seifert, Boulesteix, Carter, & Chollet, 2004).

In the current study, the nature of the leg kick in relation to the arm stroke was examined using a two-dimensional analysis approach. In able-bodied front crawl swimming the hand follows a three-dimensional movement pattern through the water (Counsilman, 1968), while the body rolls about its long axis (Yanai, 2003) and the lower limbs scribe an arc rolling about the same axis (Sanders & Psycharakis, 2009). In the current study, it was not possible to accurately determine the three-dimensional kinematics of the single-arm amputees' front crawl stroke. To compensate for their anatomical deficiency, it is apparent that unilateral arm amputee swimmers have unique, adapted variations in their front crawl stroke. However, it is not clear whether some of the variations exhibited by these swimmers (e.g., differences in arm trajectory) are more conducive to successful swimming performance than others. Further study, using accurate three-dimensional analysis techniques, is needed to fully examine the kinematics of single-arm amputee front crawl swimmers.

5.6 Summary and Conclusion

The results from this study show that increases in swimming speed corresponded with increases in stroke frequency and kick frequency. With an increase in swimming speed, swimmers did not change the number of kicks they performed per arm stroke cycle. When sprinting, swimmers predominantly used a six-beat leg kick (n = 10), although four-beat (n = 2) and eight-beat leg kicks (n = 1) were also used. There was significant temporal asymmetry between the swimmers' affect- and unaffected-arm stroke phases. In contrast, the kicking phases between legs were symmetrical. Inter-arm and inter-leg coordination did not change with an increase in swimming speed. Swimmers displayed asymmetrical leg-to-arm coordination between both sides of the body, as a consequence of asymmetrical inter-arm coordination and symmetrical inter-leg coordination. By rhythmically aligning their leg kicks with particular arm stroke phases, unilateral arm amputee front crawl swimmers might enhance performance and may maintain the stable repetition of their overall arm stroke cycle.

CHAPTER SIX

KINEMATICS OF THE FRONT CRAWL ARM ACTION AT SPRINT AND DISTANCE PACE

This chapter examines whether the three-dimensional, spatio-temporal nature of the upper extremity limb movements of single-arm amputee front crawl swimmers is influenced by 50 m and 400 m paced swimming. The inter-relationships between selected upper extremity kinematics are also assessed. The duration of arm stroke phases, the linear and angular displacement of the limbs and the linear velocities of the upper extremity segments are discussed. Chapter 6 relates to academic aim 4, in Section 2.13.

6.1 Abstract

The primary aim of this study was to determine whether the upper extremity kinematics of competitive unilateral arm amputee front crawl swimmers differed between sprint- and distance-paced swimming. The secondary aim was to examine the inter-relationships between selected upper extremity kinematics and swimming performance. Ten highly-trained swimmers were filmed using six synchronised cameras (four under and two above water) during two 25 m front crawl trials performed at 50 m and 400 m pace. Upper extremity kinematics were not generally different between swimming paces. The amputees' hand followed a more linear underwater trajectory, when compared to the hand paths of able-bodied swimmers. During the Insweep of the unaffected-arm, the amputees flexed their elbow less and exhibited less horizontal shoulder flexion and less shoulder roll than that exhibited by able-bodied swimmers. During the same phase, the amputees' inward hand velocity was much lower than that of able-bodied swimmers. These findings imply that single-arm amputee front crawl swimmers do not use pronounced medial hand movements during their Insweep. This may be due to swimmers needing less medially directed hydrodynamic force to control body roll or them relying more on a backward hand movement to generate propulsion. The amputees pulled their affected-arm through the water differently to the upper-arm segment of their unaffected-arm. When viewed from the front, swimmers pulled their affected-arm through the water: (1) in a wide arc outside the shoulder-line ($n = 4$); (2) underneath and in-line with the shoulder ($n = 4$); or (3) in a narrow arc inside the shoulder-line ($n = 2$). The amputees used more shoulder roll during the recovery of their unaffected-arm than during the affected-arm recovery. Although there was a moderate negative correlation between swimming speed and stroke length, swimmers who had the longest strokes had the smallest arm slippage and exhibited the lowest backward arm velocities, relative to the water, during the middle part of the underwater stroke.

6.2 Introduction

Sprint and distance front crawl swimmers execute an underwater S-shaped trajectory with their left hand and an inverted S-shaped trajectory with their right hand to propel themselves forward through the water (Maglischo et al., 1988; McCabe et al., 2011; Payton & Lauder, 1995; Perrier & Monteil, 2004). These movements are generally accepted as desirable features of able-bodied front crawl swimming technique (Counsilman, 1968; Lui et al., 1993; Schleihauf, Gray, & DeRose, 1983; Schleihauf et al., 1988) and are achieved by swimmers rotating and translating their arms vertically and medio-laterally in the water (Payton et al., 1997), perpendicular to the swimming direction as the body rolls about its long axis (Yanai, 2003). During the hand trajectory, the hand and forearm segments accelerate to generate propulsion (Berger et al., 1995; Bixler & Riewald, 2002). Thus the velocity at which the hand and forearm segments move relative to the water is an important determinate for successfully generating propulsion (Payton et al., 1999; 2002) and as a consequence the successful forward progression of the swimmer (Toussaint & Beek, 1992).

Competitive swimmers with a single, elbow-level amputation are clearly disadvantaged when compared to able-bodied swimmers, as they are deprived of an important propelling surface (hand plus forearm segment). If these body segments are missing, swimmers must rely on the surface area of the upper-arm to generate propulsion (Prins & Murata, 2008). Theoretically, it has been demonstrated that it is possible for the affected-limb of a front crawl swimmer with a single elbow-level amputation to generate propulsion (Lecrivain et al., 2008). However, at swimming speeds higher than 1 $m \cdot s^{-1}$, the ability of the affected-arm (upper-arm) to generate propulsion effectively has been shown to decrease (Lecrivain et al., 2010). In practice therefore, uncertainty remains as to whether the affected-arm of a unilateral arm amputee can contribute effectively to propulsion. For unilateral arm amputee swimmers, the increase in intra-cyclic swimming speed observed during the underwater pull of the affected-arm did not correlate with the shoulder extension velocity of the same arm (Payton & Wilcox, 2006). This suggests that factors other than limb speed, such as the timing and trajectory of the underwater arm pull, may be more important in determining the effectiveness of the stroking technique.

When the movement patterns of persons with physical disabilities are observed, it is apparent that they have unique, adapted variations in their stroking technique, which compensate for existing anatomical deficiencies (Prins & Murata, 2008). Indeed, within a homogenous group of highly-trained unilateral arm amputees different inter-arm coordination strategies were evident between the swimmers' affected- and unaffected-arm stroke (Osborough et al., 2010). At different swimming speeds, competitive unilateral arm amputee swimmers use various movement patterns and motor control strategies to compensate for their physical impairment.

To fully describe the upper extremity movement patterns of single-arm amputee swimmers, accurate temporal and kinematic data are required. As previous studies into the characteristics of unilateral arm amputee front crawl swimmers have only used two-dimensional analysis techniques, they have been unable to fully and accurately describe the spatial movement patterns employed by these swimmers. Using three-dimensional analysis techniques, the primary aim of this study was to determine whether the upper extremity kinematics of competitive unilateral arm amputee front crawl swimmers differed between sprint- and distance-paced swimming. The secondary aim was to examine the inter-relationships between selected upper extremity kinematics and swimming performance.

6.3 Methods

6.3.1 Participants

Ten (2 male and 8 female) competitive swimmers (age 16.8 ± 3.3 yrs; height 1.68 ± 0.09 m; mass 63.9 ± 14.2 kg), whose mean long course 50 m front crawl personal best time was 33.1 ± 3.1 seconds, participated in this study. The best times of the two male participants were ranked between 24th and 30th in the world for the long course 50 m front crawl (International Paralympic Committee, 2008). For the same event, two of the female participants were ranked between 5th and 7th in the world and four were ranked between 38th and 45th in the world. The best times of the remaining two females were ranked outside the top 60 in the world.

All the participants were congenital single-arm amputees (4 right-arm; 6 left-arm), at the level of the elbow (Appendix 1). Nine of the swimmers competed in the International Paralympic Committee S9 Class for front crawl; one male swimmer competed in the S8 Class due to an additional impairment of one of his lower limbs. The procedure for the data collection was approved by the Institutional Ethics Committee. All participants provided either written informed consent or, in the case of minors, parental written consent before taking part in the study.

6.3.2 Data Collection

After a standardised 600 m warm up, participants were randomly allocated into one of two test groups. Each participant completed two 25 m front crawl trials, from a push start, at intervals of 3 minutes. One of these trials was performed at 50 m swimming pace and the other was performed at 400 m swimming pace. These paces replicated those swum during IPC competition events. The trials were performed in a counterbalanced fashion (e.g., group 1: 50 m then 400 m pace; group 2: 400 m then 50 m pace) and were manually recorded by two experienced timekeepers. To control for the effects of the breathing action on the swimming stroke, participants were instructed not to take a breath through a 10 m test section of the 25 m pool. Situated within this 10 m section was a calibrated performance volume, though which each participant swam (Figure 6.1).

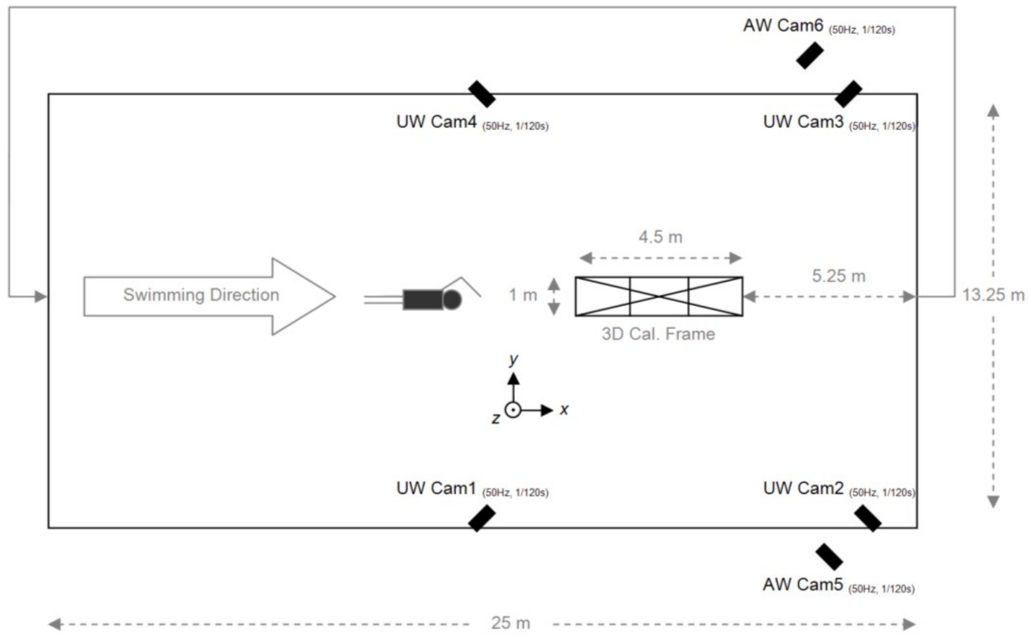

Figure 6.1. Plan view of the three-dimensional filming set-up.

The performance volume was calibrated with a 6.75 m^3 calibration frame (Figure 6.2) with orthogonal axes (4.5 m × 1.0 m × 1.5 m, for the swimming direction (*X*), the left-lateral direction (*Y*) and the vertical direction (*Z*) respectively), positioned so that half the frame was above and half below the water. The frame contained 92 control points (3 cm diameter polystyrene spheres) of known location distributed randomly throughout the volume (46 above and 46 below the water).

The calibration set-up has been described in detail and the accuracy and reliability of the calibration procedures, using this particular frame, have been established by Psycharakis et al., (2005). They concluded that the small reconstruction errors were similar to, or better than, other studies that used similar performance volumes (e.g., Coleman & Rankin, 2005).

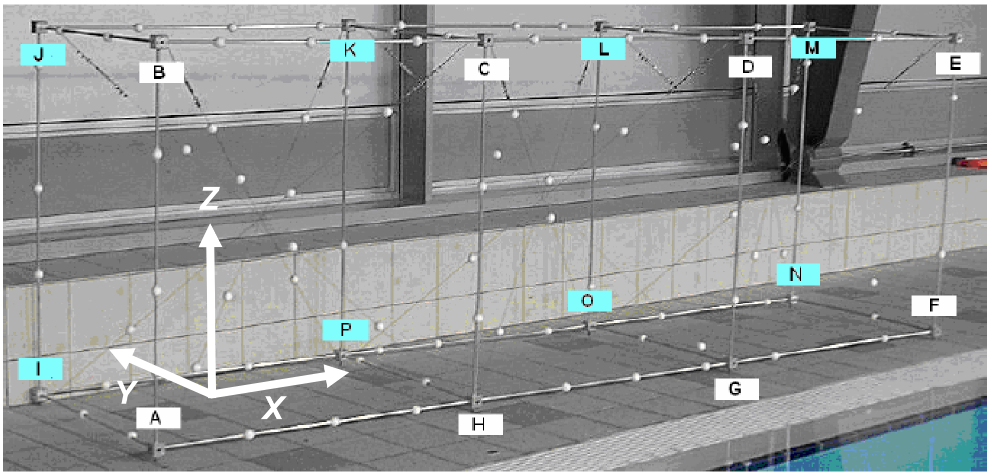

Figure 6.2. Three-dimensional calibration frame (4.5 m × 1.0 m × 1.5 m).

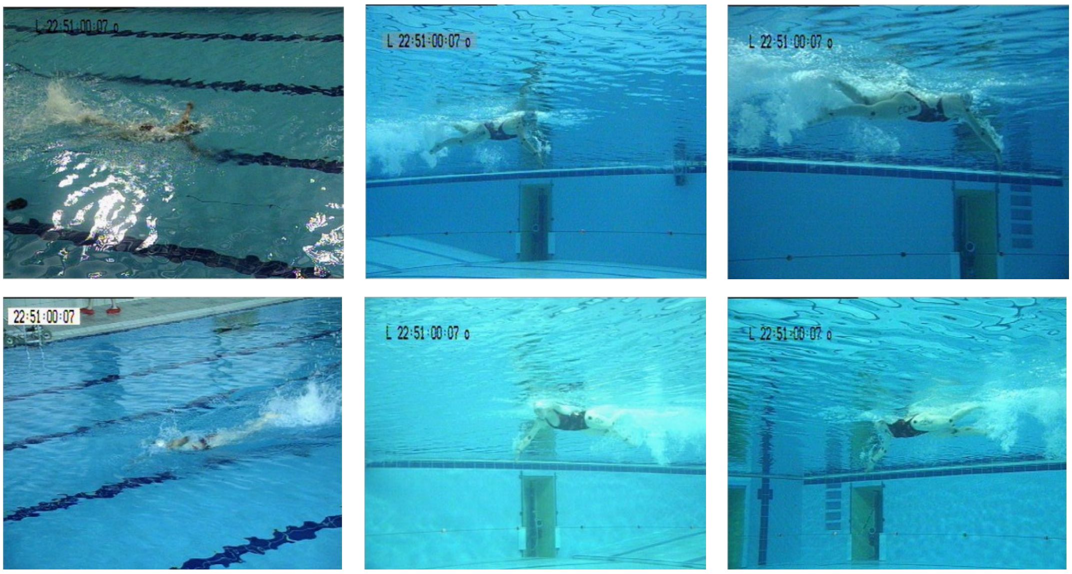

Figure 6.3. View from the six synchronised JVC KY32 CCD cameras, during one swimming trial.

Each participant's trial through the performance volume was recorded with six stationary and synchronised JVC KY32 CCD cameras, operating at 50 Hz with a shutter speed of 1/120 s. Four cameras were below and two were above the water (Figure 6.3). The time codes were displayed on each frame of all video recordings to facilitate subsequent processing.

6.3.3 Data Processing

A participant's full stroke cycle (defined as the period from water entry of the hand of the unaffected-arm, to the next entry of that hand) from within the performance volume, at 50 m and 400 m swimming pace, was used for analysis. A thirteen-segment model of the body was defined by eighteen body landmarks (vertex; shoulder; elbow; unaffected-wrist; hip; knee; ankle; metaphalangeal joints; big toes; the most distal point of the affected-arm and the end of the unaffected-middle finger). For each separate camera view, the estimated locations of these points were manually digitised, at a sampling frequency of 50 Hz using SIMI Motion 7.2 software (SIMI Reality Motion Systems GmbH, Unterschleißheim, Germany). Before filming, the skin overlaying these points was marked with black waterproof oil- and wax-based cream (Grimas Crème Make Up), applied using a 45 mm diameter sponge, to help estimate their location.

Image coordinates were transformed into three-dimensional object-space coordinates using a Direct Linear Transformation (DLT) algorithm (Abdel-Aziz & Karara, 1971; Kwon, 1998) incorporated within the SIMI Motion software. The accuracy of locating submerged body landmarks was improved by having four cameras, compared to just two. This meant that for the vast majority of the digitised frames, each marker was clearly visible from at least two cameras, minimising the incidence of "guessed points" being used in the DLT calculation. The calculated three-dimensional coordinates were then smoothed using a 2nd order low pass Butterworth filter. A cut-off frequency of 6-8 Hz was used and selected through a visual inspection of the fit (Winter, 1990). Mean absolute reconstruction errors in the three-dimensional coordinates were 4 mm, 3.5 mm and 4 mm in the X, Y and Z directions respectively. When expressed relative to the dimensions of the performance volume, the corresponding percentage errors were 0.09%, 0.35% and 0.27%. These reconstruction errors in this study were similar to or lower than those reported in studies by Coleman and Rankin, (2005), Payton et al., (1999; 2002) and Psycharakis et al., (2005).

6.3.4 Body Segment Parameter Calculations

Accurate body segment parameter (BSP) data for individual participants were obtained with the use of the elliptical zone method of Jenson (1976) applied using the "eZone" software programme developed by Deffeyes and Sanders (2005). Three 4.0 megapixel digital cameras (Nikon E4200 and Canon Ixus 400), with an exposure time of 1/60 s, ISO 200 and focal length of 23 mm were used to photograph the participants. Each camera was fixed to a horizontally-levelled tripod, set at a height of 1 m. The cameras were positioned such that the frontal and sagittal planes of each participant were viewed simultaneously (Figure 6.4). To minimise image distortion whilst maintaining a large image of the participant, the perpendicular distance from the centre of the space to each of the cameras was 12 m. To scale the recorded photographs a vertical and horizontal reference scale consisting of a series of 200 mm alternating white and black bands was positioned in the same plane as the participants' mid-frontal and mid-sagittal planes. Based on digitised segment landmarks, the "eZone" software defined each participant's body as a fifteen-segment model (head, neck, thorax, arm, forearm, hand, thigh, shank, and foot segments). To determine shape fluctuation within segments, each segment was divided into 2 cm elliptical zones. Segment densities were assumed to be uniform and as reported by Dempster (1955). Individualised BSP data were input to the SIMI Motion software for the calculation of each participant's whole-body mass centre position.

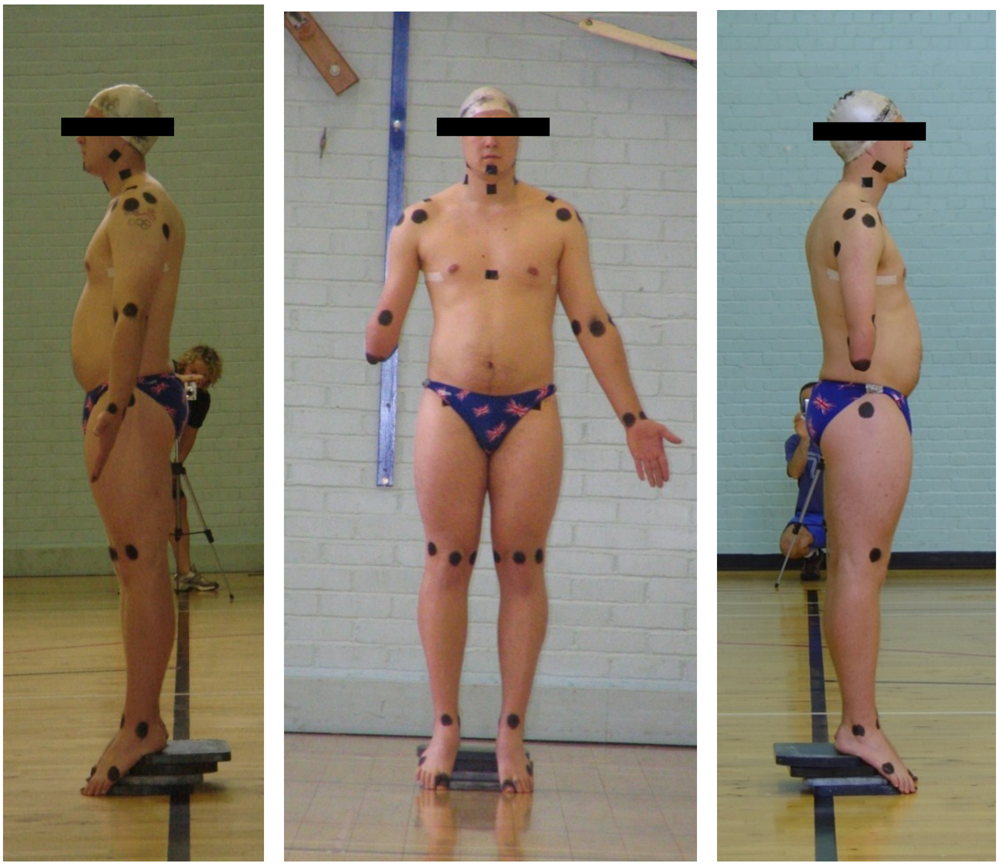

Figure 6.4. Photographs of participant's frontal and sagittal planes for use with the "eZone" software programme**.**

The accuracy and reliability of the "eZone" calculations used in this study have been previously reported in the literature (Psycharakis et al., 2010). For eleven male international and national swimmers, the mean (± SD) difference between whole body mass calculated using the "eZone" software and that measured using scales was -0.2 ± 0.9 kg or -0.3 ± 1.3% (expressed as a percentage of real body mass). These differences were similar to, or smaller than, other studies using the elliptical zone method (e.g., Jensen, 1978; Sanders et al., 1991). Reliability of the "eZone" calculations was obtained by Psycharakis et al. (2010) through repeated digitising (10 times) of the same swimmer and calculation of the standard deviation for whole body mass. This was 0.4 kg or 0.31% of the mean body mass. In the current study, the BSP data obtained using the "eZone" software was assumed to be both valid and repeatable.

6.3.5 Definition of Variables

For comparisons against the literature, the stroke cycle of the unaffected-arm (hand entry to next hand entry) was divided into five phases (Maglischo, 2003; Payton & Lauder, 1995; Payton et al., 1999):

(1) *Glide*: from where the hand entered the water to where the elbow of the opposite arm exited the water.

(2) *Downsweep*: from the end of the Glide to where the hand reached its most lateral position.

(3) *Insweep*: from the end of the Downsweep to where the hand reached its most medial position.

(4) *Upsweep*: from the end of the Insweep to where the hand reached its most backward position.

(5) *Recovery*: from the end of the Upsweep to next hand entry.

For inter-arm comparisons, the stroke cycle of both upper-arms (elbow entry to next elbow entry) was divided into four phases (Chollet et al., 2000; McCabe et al., 2011; Seifert et al., 2004):

(A) *Glide*: from where the elbow joint centre entered the water to where it began moving horizontally backward relative to the water.

(B) *Pull*: from the end of the Glide to where the elbow joint centre was vertically aligned with the shoulder joint centre.

(C) *Push*: From the end of the Pull to where the elbow joint centre ended its horizontal backward movement relative to the water.

(D) *Recovery*: from the end of the Push to next elbow entry.

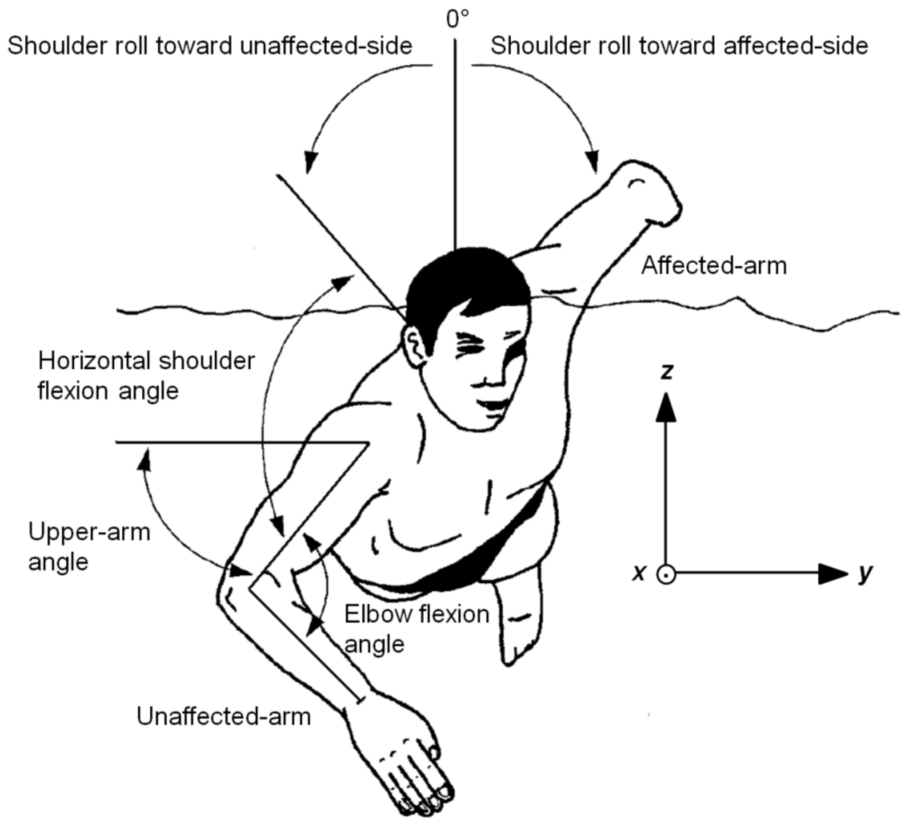

Figure 6.5. Shoulder roll, horizontal shoulder flexion, upper-arm and elbow angle convention for a swimmer who has a left arm amputation (adapted from Payton et al., 1999).

The following stroke parameters were calculated from the three-dimensional analysis of one stroke cycle, at each participant's 50 m and 400 m front crawl swimming pace: 1) *Swimming speed* ($m \cdot s^{-1}$): mean forward horizontal speed of the participant's mass centre during the stroke cycle; 2) *Stroke frequency* (Hz): number of stroke cycles performed in one second; 3) *Stroke length* (m): distance that the participant's mass centre travelled down the pool during the stroke cycle.

The following variables were used to describe the kinematics of the unaffected-arm; 4) *Hand depth* (m): vertical (*Z*-axis) displacement of the hand mass centre from water entry to deepest point; 5) *Hand width* (m): medial (*Y*-axis) displacement of the hand mass centre during the Insweep phase; 6) *Absolute hand pull length* (*slippage*) (m): backward (*X*-axis) displacement of the hand mass centre from its most forward position to its most backward position relative to the water; 7) *Relative hand pull length* (m): backward (*X*-axis) displacement of the hand mass centre from its most forward position to its most backward position relative to the unaffected-shoulder; 8) *Hand velocity* ($m \cdot s^{-1}$): velocity of the hand mass centre relative to the water; 9) *Elbow flexion angle* (°): angle between the shoulder-to-elbow position vector and the elbow-to-wrist position vector of the unaffected-arm (Figure 6.5).

The following variables were used to describe the kinematics of both the affected- and unaffected-arm: 10) *Elbow depth* (m): vertical (*Z*-axis) displacement of the elbow joint centre from water entry to deepest point; 11) *Elbow width* (m): lateral (*Y*-axis) displacement of the elbow joint centre from water entry to widest point; 12) *Absolute elbow pull length* (*slippage*) (m): backward (*X*-axis) displacement of the elbow joint centre from its most forward position to its most backward position relative to the water; 13) *Relative elbow pull length* (m): backward (*X*-axis) displacement of the elbow joint centre from its most forward position to its most backward position relative to the shoulder; 14) *Elbow recovery height* (m): vertical (*Z*-axis) displacement of the elbow joint centre from water exit to highest point; 15) *Elbow recovery width* (m): lateral (*Y*-axis) displacement of the elbow joint centre from water exit to widest point; 16) *Elbow velocity* ($m \cdot s^{-1}$): velocity of the elbow joint centre relative to the water; 17) *Upper-arm angle* (°): angle between the horizontal (*Y*-axis) and the projection of the shoulder-to-elbow position vector onto the *Y-Z* plane (Figure 6.5); 18) *Horizontal shoulder flexion angle* (°): angle between the shoulder-to-elbow position vector and a line perpendicular to the shoulder-to-shoulder position vector, projected onto the *Y-Z* plane (Figure 6.5), calculated in the SIMI Motion software; 19) *Shoulder roll angle* (°): angle between the horizontal (*Y*-axis) and the shoulder-to-shoulder position vector, projected onto the *Y-Z* plane (Figure 6.5).

6.3.6 Statistical Analyses

Means and standard deviations were computed for all the measured variables. Normal distribution of the data was assessed using the Shapiro-Wilks test. Paired *t*-tests were used to compare differences in the following unaffected-arm variables between the 50 m and 400 m pace: swimming speed; stroke frequency; stroke length; Glide, Downsweep, Insweep, Upsweep and Recovery times (expressed as a percentage of the total stroke time); hand depth; hand width; hand pull length (absolute and relative); peak downward and peak backward hand velocity during the Downsweep; peak inward and peak backward hand velocity during the Insweep; peak outward and backward hand velocity during the Upsweep; elbow flexion, upper-arm, horizontal shoulder flexion and shoulder roll angles at the start and end of the Insweep.

Multivariate general linear modelling (GLM) tests were used to compare the following variables between the affected- and unaffected-arm and between the 50 m and 400 m pace: Glide, Pull, Push and Recovery time (expressed as a percentage of the total stroke time); elbow depth; elbow width; elbow pull length (absolute and relative); elbow recovery height; elbow recovery width; peak downward, peak backward and peak upward elbow velocity and shoulder roll angle at the instant when the elbow joint centre was at its deepest position. Multiple comparisons were made with the Bonferroni *post hoc* test.

Relationships between selected upper extremity kinematics and swimming performance were examined for the amputee swimmers. Six separate forward stepwise multiple regression analyses were used between swimming speed, stroke length and stroke frequency, and between stroke frequency and the stroke phase durations for each arm, at 50 m and 400 m pace. Correlations were calculated among selected upper extremity kinematics at 50 m and 400 m pace. When normal distribution was met, the Pearson Product correlation test was used, and when not, the Spearman Rank correlation test was used. In all comparisons, the level of significance was set at $p < .05$. Statistical analysis procedures were performed using SPSS 18.0 software.

Intra-tester reliability of the digitising process was established by performing five repeat digitisations on separate days of a randomly selected trial. Inter-tester reliability of the digitising process was established by two experienced analysts separately digitising the same randomly selected trial. For both intra- and inter-tester reliability, the coefficients of repeatability (Bland & Altman, 1986) were obtained for hand displacement, affected-elbow velocity and shoulder roll angle. This involved calculating the 95% limits of agreement (± 1.96 standard deviations of the differences) between each data set (Appendix VI). The root mean square (RMS) differences between the repeated measurement data sets were also calculated.

6.4 Results

Low intra-tester and inter-tester repeatability coefficients and RMS differences demonstrated that the digitised data were both reliable and objective. The intra-tester and inter-tester repeatability coefficients for hand displacement were 0.008 m and 0.007 m respectively. The corresponding RMS differences were 0.009 m and 0.004 m. For the affected-elbow velocity, the intra-tester and inter-tester repeatability coefficients were 0.06 $m \cdot s^{-1}$ and 0.05 $m \cdot s^{-1}$ respectively. The corresponding RMS differences for the affected-elbow velocity were 0.06 $m \cdot s^{-1}$ and 0.04 $m \cdot s^{-1}$. The intra-tester and inter-tester repeatability coefficients for shoulder roll angle were 1.4° and 1.3° respectively. The corresponding RMS differences were 1.8° and 1.2°. The determination of intra- and inter-tester repeatability coefficients and RMS differences are presented in Appendix VI.

Stroke frequency was significantly higher (0.80 ± 0.12 Hz vs. 0.69 ± 0.10 Hz; $p < .01$) and stroke length significantly shorter (1.67 ± 0.16 m vs. 1.74 ± 0.13 m; $p < .05$)

during the 50 m pace trial, when compared to the 400 m pace trial (1.32 ± 0.14 $m \cdot s^{-1}$ vs. 1.19 ± 0.11 $m \cdot s^{-1}$; $p < .01$).

6.4.1 Unaffected-arm kinematics

No notable differences between conditions were observed in relative stroke phase durations or hand displacement data for the unaffected-arm (Table 6.1). The hand on the unaffected-arm followed a similar trajectory for both the 50 m and 400 m swimming trials (Figure 6.6). Individual swimmer's plots for upper-limb trajectories during the 50 m and 400 m trials can be found in Appendix V.

Participants generated significantly higher peak backward hand velocity during the Insweep phase, when swimming at their 50 m pace compared to their 400 m pace (1.35 ± 0.17 $m \cdot s^{-1}$ vs. 1.19 ± 0.28 $m \cdot s^{-1}$; $p < .05$). Peak hand velocities during the Downsweep and Upsweep phases were similar between the two conditions (Table 6.1).

During the Insweep in the 50 m trial (Figure 6.7), the elbow flexed through 34 ± 10° and the shoulder horizontally flexed through 28 ± 10°. The respective values in the 400 m trial were 34 ± 12° and 25 ± 12°. Participants rolled back towards the neutral position (0° in Figure 6.5) when they performed the Insweep. The shoulder roll angles, together with the upper-arm, elbow and horizontal shoulder flexion angles at the start and end of the Insweep were very similar under both conditions.

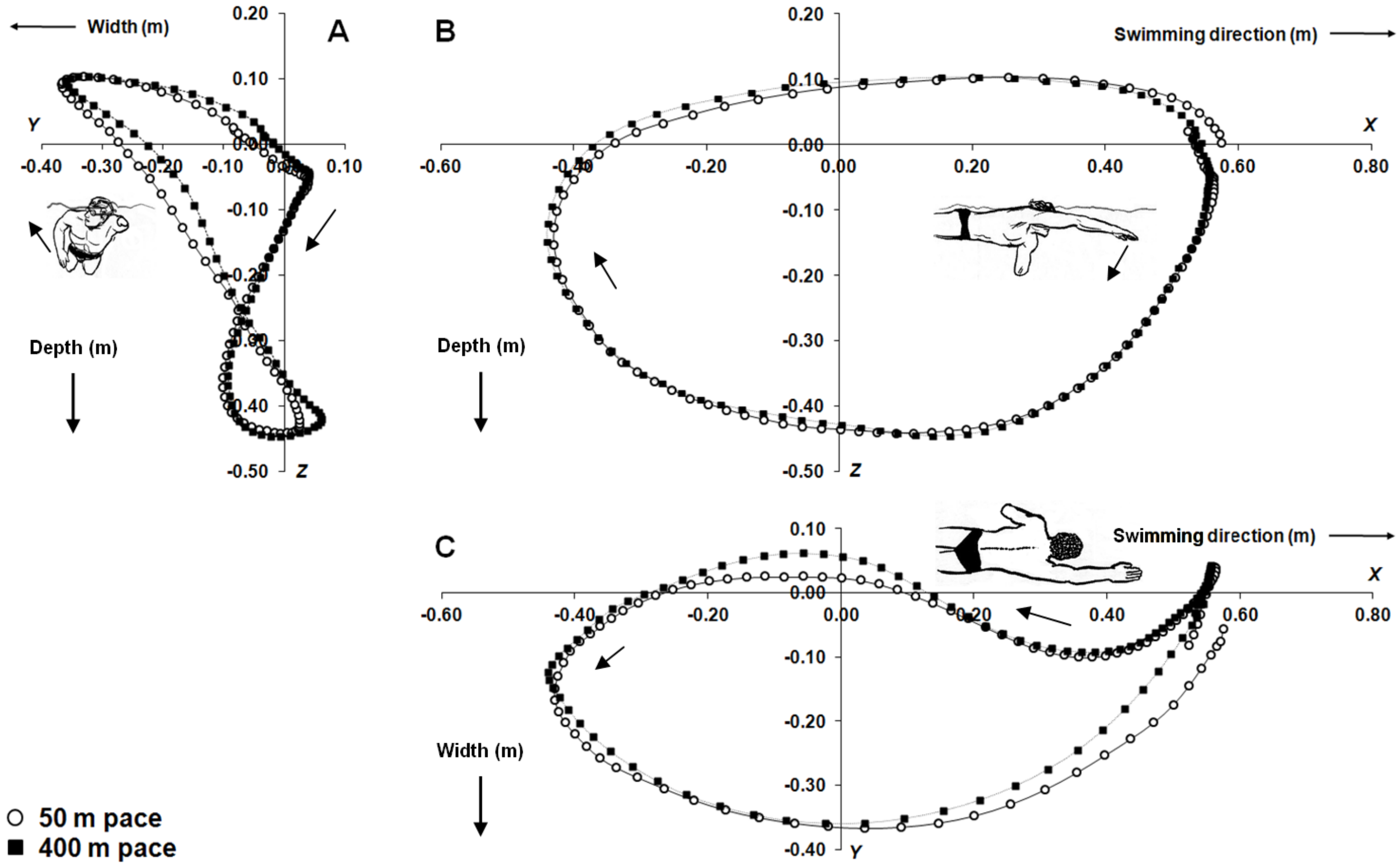

Figure 6.6. Mean normalised front (A), side (B) and above (C) views of the swimmers' right hand (on unaffected-arm) trajectory, relative to the shoulder, for the 50 m and 400 m swimming paced trials.

Table 6.1. Means (M) and standard deviations (SD) of stroke parameters, hand stroke phase durations (expressed as a percentage of stroke time), hand displacement and hand velocity for the unaffected-arm, for the 50 m and 400 m swimming paced trials.

Dependent variables	Unaffected-arm			
	50 m pace		**400 m pace**	
	M	***SD***	***M***	***SD***
Swimming speed ($m \cdot s^{-1}$)	1.32	0.14	1.19	0.11 [a]
Stroke frequency (Hz)	0.80	0.12	0.69	0.10 [a]
Stroke length (m)	1.67	0.16	1.74	0.13 [b]
Glide (% time)	23	6	20	7
Downsweep (% time)	17	6	17	6
Insweep (% time)	13	6	14	5
Upsweep (% time)	13	3	13	3
Recovery (% time)	34	6	36	6
Hand depth (m)	0.59	0.07	0.59	0.07
Hand width (m)	0.17	0.05	0.17	0.06
Absolute hand pull length (m)	0.40	0.06	0.42	0.06
Relative hand pull length (m)	1.04	0.07	1.03	0.07
During Downsweep				
Peak downward hand velocity ($m \cdot s^{-1}$)	1.35	0.28	1.23	0.23
Peak backward hand velocity ($m \cdot s^{-1}$)	0.74	0.27	0.62	0.36
During Insweep				
Peak inward hand velocity ($m \cdot s^{-1}$)	1.09	0.31	1.15	0.35
Peak backward hand velocity ($m \cdot s^{-1}$)	1.35	0.27	1.19	0.28 [b]
During Upsweep				
Peak outward hand velocity ($m \cdot s^{-1}$)	1.00	0.50	1.04	0.45
Peak backward hand velocity ($m \cdot s^{-1}$)	1.37	0.22	1.34	0.17

[a] Denotes significant difference ($p < .01$) between 50 m and 400 m pace.

[b] Denotes significant difference ($p < .05$) between 50 m and 400 m pace.

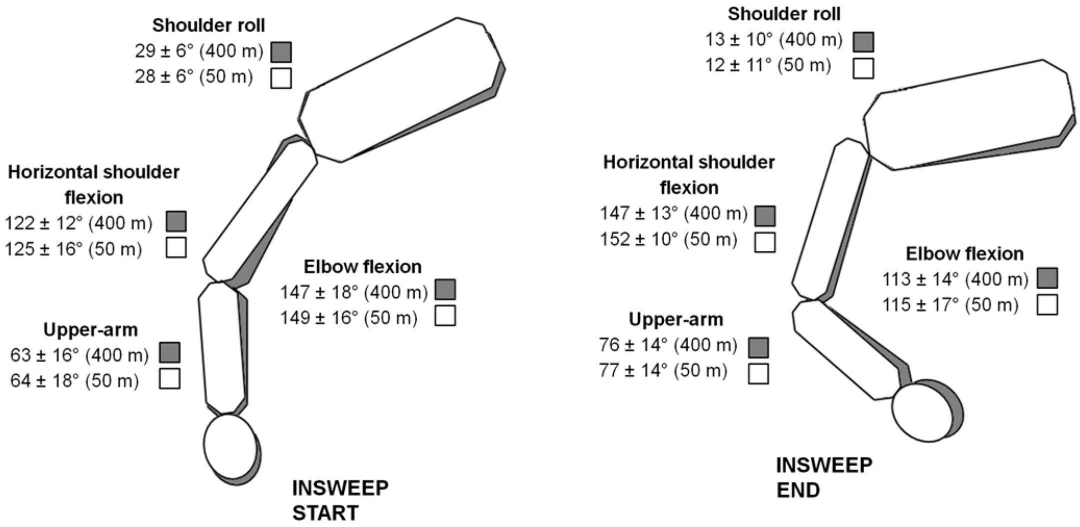

Figure 6.7. Front view of the upper extremity position (mean ± SD) at the start and end of the unaffected-arm's Insweep phase, for the 50 m and 400 m swimming paced trials.

6.4.2 Affected- and unaffected-arm kinematics

Significant differences between the relative durations of the affected- and unaffected-arm stroke phases were evident between the two conditions (Table 6.2). At 50 m pace, the affected-arm's Push (10 ± 1% vs. 9 ± 1%) and Recovery (47 ± 9% vs. 45 ± 10%) were relatively longer ($p < .05$) than at 400 m pace. The unaffected-arm's Pull (10 ± 2% vs. 8 ± 4%) and Recovery (46 ± 6% vs. 44 ± 4%) at 50 m pace were relatively longer ($p < .05$), and the Push (9 ± 2% vs. 11 ± 2%) relatively shorter ($p < .05$) in duration than at 400 m pace. At 50 m pace, the unaffected-arm's Pull was proportionally longer ($p < .05$) than the affected-arm's Pull (10 ± 2% vs. 8 ± 2%). At 400 m pace, the unaffected-arm's Push was relatively longer in duration than the affected-arm's Push (11 ± 2% vs. 9 ± 1%; $p < .05$).

Participants pulled their affected-arm through and over the water differently to the upper-arm segment of their unaffected-arm (Table 6.2). Unaffected-arm elbow depth was significantly shallower (0.33 ± 0.06 m vs. 0.42 ± 0.05 m; $p < .05$) and elbow pull length shorter (0.10 ± 0.05 m vs. 0.24 ± 0.04 m; $p < .05$), relative to the water, than the elbow of the affected-arm. Unaffected-arm elbow recovery was significantly higher (0.21 ±0.05 m vs. 0.14 ± 0.04 m; $p < .05$) and narrower (0.10 ± 0.04 m vs. 0.22 ± 0.06 m; $p < .05$) compared to that of the affected-arm's elbow. No notable differences in elbow displacement were observed between 50 m and 400 m pace (Figure 6.8).

Participants exhibited considerably higher elbow velocities for their affected-arm than for their unaffected-arm (Table 6.2). Peak downward and peak backward elbow velocities of the affected-arm were three times greater than those of the unaffected-arm. Much smaller and non-significant differences were evident between the peak upward elbow velocities of the affected- and unaffected-arm. These remained similar at 50 m and 400 m pace. Only peak downward elbow velocity during the Pull was influenced by swimming pace. When swimming at 50 m pace, peak downward elbow velocity was significantly higher ($p < .05$) than at 400 m pace, for both the unaffected- and affected-arm.

Swimming at different speeds did not influence the orientation of the participants' upper extremity limbs, when the elbows were at their deepest position (Figure 6.9). Differences in upper-arm and shoulder horizontal flexion angles between arms were evident but not significant. Shoulder roll angle was significantly greater ($p < .05$) on the affected-side (41 ± 13°) compared to the unaffected-side (26 ± 11°).

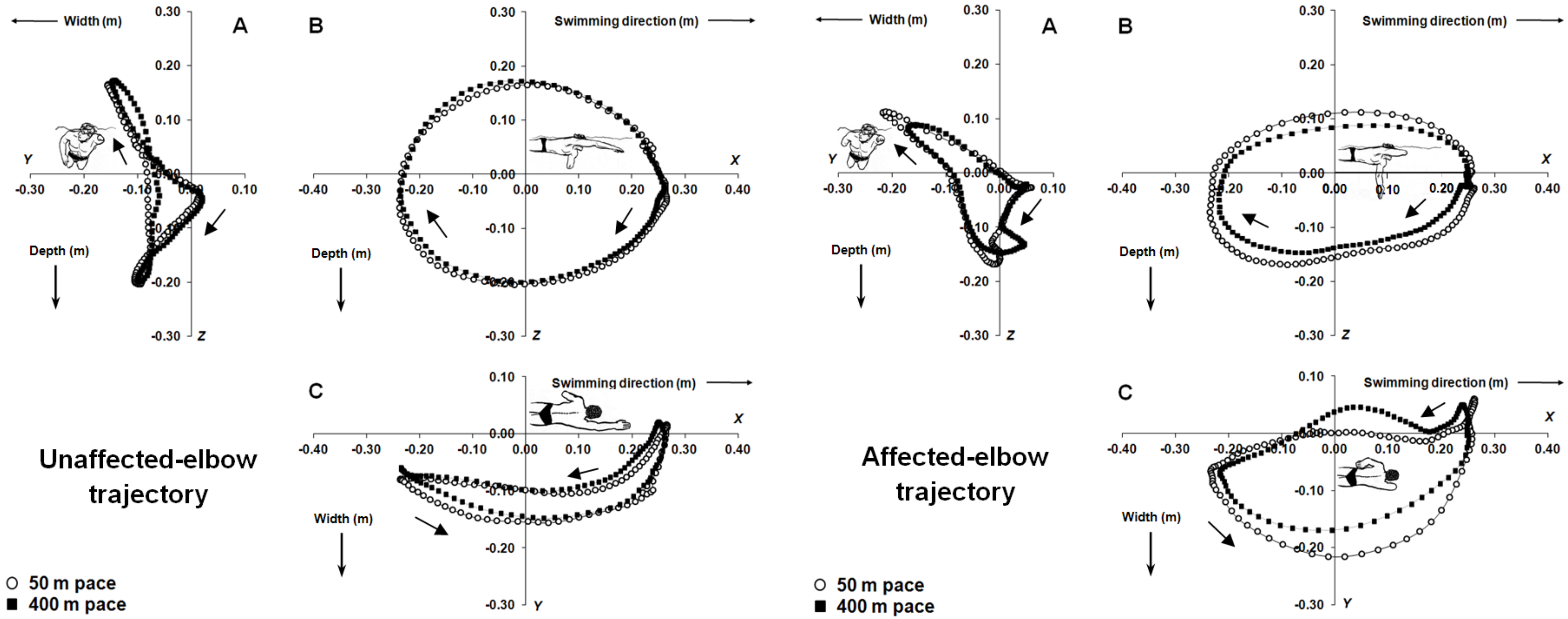

Figure 6.8. Mean normalised front (A), side (B) and above (C) views of the swimmers' elbow trajectory, relative to the shoulder, for the 50 m and 400 m swimming paced trials. Left-hand side: unaffected-elbow. Right-hand side: affected-elbow.

Table 6.2. Means (M) and standard deviations (SD) of stroke phase durations (expressed as a percentage of stroke time), elbow displacement and elbow velocity for the affected- and unaffected-arm, for the 50 m and 400 m swimming paced trials.

Dependent variables	Unaffected-arm				Affected-arm			
	50 m pace		400 m pace		50 m pace		400 m pace	
	M	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***
Glide (% time)	35	6	37	4	35	10	38	11
Pull (% time)	10	2 [a, b]	8	4	8	2	8	1
Push (% time)	9	2 [a]	11	2 [b]	10	1 [a]	9	1
Recovery (% time)	46	6 [a]	44	4	47	9 [a]	45	10
Elbow depth (m)	0.33	.06 [b]	0.34	.06 [b]	0.42	.05	0.42	.04
Elbow width (m)	0.18	.07	0.17	.07	0.17	.05	0.21	.04
Abs. elbow pull length (m)	0.09	.05 [b]	0.10	.05 [b]	0.23	.04	0.24	.04
Rel. elbow pull length (m)	0.54	.05	0.52	.04	0.53	.05	0.52	.04
Elbow recovery height (m)	0.20	.05 [b]	0.21	.04 [b]	0.14	.03	0.14	.04
Elbow recovery width (m)	0.10	.04 [b]	0.10	.03 [b]	0.21	.06	0.22	.05
Peak elbow velocities ($m \cdot s^{-1}$)								
Downward (during Pull)	0.53	.20 [a, b]	0.40	.21 [b]	1.76	.24 [a]	1.50	.29
Backward (during stroke)	0.55	.29 [b]	0.59	.25 [b]	1.64	.32	1.52	.32
Upward (during Push)	1.47	.14	1.43	.25	1.61	.25	1.44	.30

[a] Denotes significant difference ($p < .05$) between 50 m and 400 m pace.

[b] Denotes significant difference ($p < .05$) between affected- and unaffected-arm.

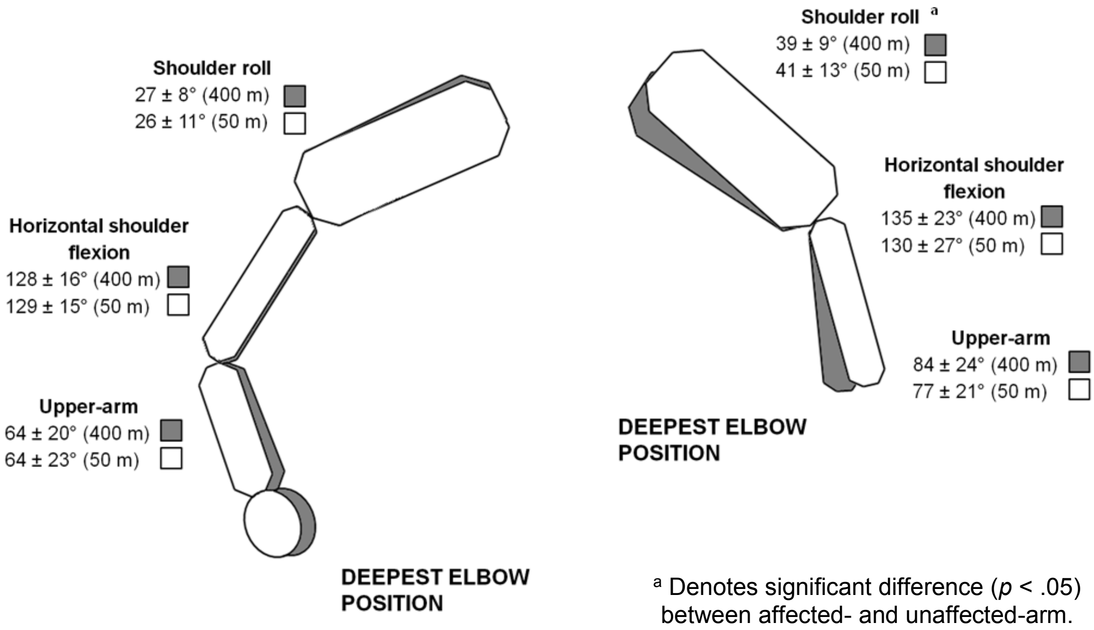

Figure 6.9. Front view of the upper extremity orientation (mean ± SD) when the elbows were at their deepest position, for the 50 m and 400 m swimming paced trials.

Mean shoulder roll angle was asymmetrical between the unaffected- and affected-side of the participants (Figure 6.10). At elbow entry of the unaffected-arm, the shoulders were rolling towards the unaffected-side away from the neutral position (0° in Figure 6.5). The shoulders continued to roll towards the unaffected-side during the Glide, such that the maximum shoulder roll angle occurred late in this phase, with the mean value for the maximum shoulder roll angle being 32 ± 7° at 50 m pace and 33 ± 6° at 400 m pace. In comparison, at elbow entry of the affected-arm, the shoulders were rolling towards the affected-side but had not reached the neutral position. The body continued to roll towards the affected-side after the Glide phase was completed. The maximum shoulder angle, on the affected-side was reached early in the Push, with the mean value for the maximum shoulder roll angle being 43 ± 8° at both 50 m and 400 m pace. The shoulders commenced rolling back towards the neutral position at the end of the Glide on the unaffected-side, and during the Push on the affected-side.

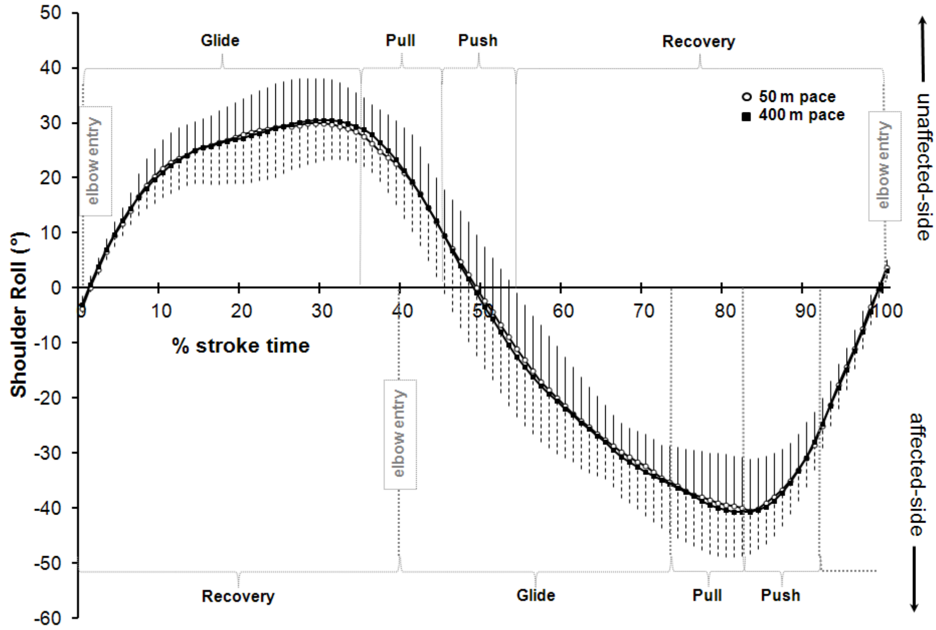

Figure 6.10. Shoulder roll angles (mean ± SD) expressed as a function of percentage stroke time, for the 50 m and 400 m swimming paced trials.

6.4.3 Inter-swimmer correlations

At 50 m pace, inter-swimmer correlations (Figure 6.11) showed that for the amputee swimmers, stroke frequency was significantly related to swimming speed (r = .74; p < .05) and stroke length was moderately related to swimming speed (r = -.33). Results from the forward stepwise multiple regression analysis revealed that as predictors, stroke frequency and stroke length accounted for 98% of the total variance in swimming speed. Stroke frequency had the larger influence, accounting for 55% of the variance, whereas stroke length accounted for 43%.

For the amputees' unaffected-arm, Glide and Recovery time were significantly related to stroke frequency at 50 m pace (r = -.89; p < .01 and r = -.85; p < .01 respectively). For this arm, the predictors of Glide, Pull and Recovery time accounted 98% of the total variance in stroke frequency. Glide time had the largest influence, accounting for 78% of the variance, followed by Recovery time (17%) and Pull time (4%). For the amputees' affected-arm, Glide and Push time were significantly related to stroke frequency (r = -.84; $p < .01$ and r = -.83; $p < .05$ respectively). For this arm, the predictors of Glide and Recovery time accounted for 95% of the total variance in stroke frequency. Glide time had the larger influence, accounting for 70% of the variance, whereas Recovery time accounted for 25%.

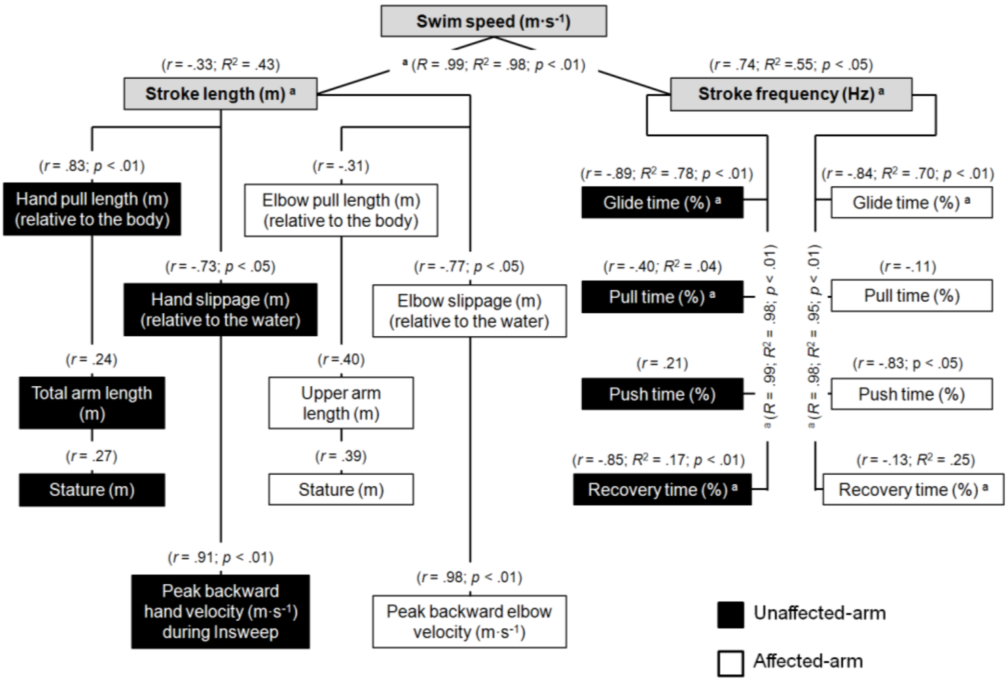

Figure 6.11. Relationships between selected upper extremity kinematics and swimming performance, for the amputee swimmers during the 50 m swimming paced trial.

[a] Predictors used in the forward stepwise multiple regression analyses. R^2 values represent the amount of variance of the criterion variable accounted for by the weighted combination of predictor variables; r values represent Pearson Product correlation coefficients.

For the amputee swimmers, stroke length at 50 m pace was positively related to hand pull length (r = .83; $p < .01$) but negatively related to hand slippage (r = -.73; $p <$ .05) and to elbow slippage (r = -.77; $p < .05$). Hand slippage was significantly related to the peak backward hand velocity attained during the Insweep (r = .91; $p < .01$). Elbow slippage was significantly related to the swimmers' peak backward elbow velocity (r = .98; p < .01). The correlations among stature, limb length, hand, and elbow pull length were low and non-significant.

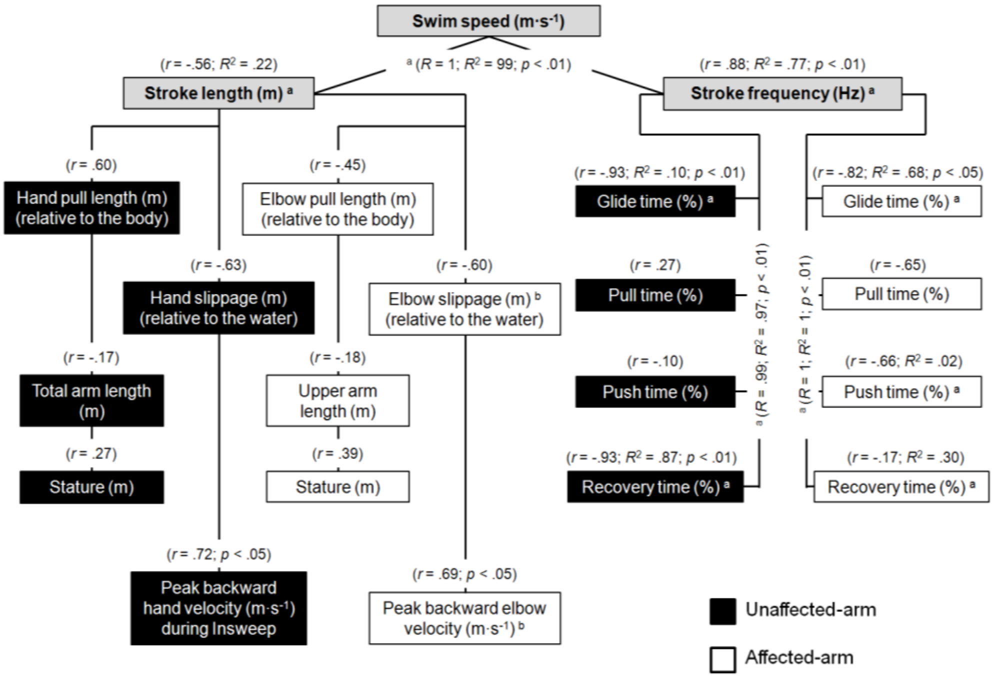

Figure 6.12. Relationships between selected upper extremity kinematics and swimming performance, for the amputee swimmers during the 400 m swimming paced trial.

[a] Predictors used in the forward stepwise multiple regression analyses. R^2 values represent the amount of variance of the criterion variable accounted for by the weighted combination of predictor variables; r values represent Pearson Product correlation coefficients.

[b] Correlations performed using Spearman Rank correlation tests.

At 400 m pace, the amputees' inter-swimmer correlations (Figure 6.12) showed that stroke frequency was significantly related to swimming speed (r = .88; p < .01) and accounted for 77% of the variance in swimming speed. Stroke length was moderately related to swimming speed (r = -.56) and accounted for 22% of the variance in swimming speed. The Glide and Recovery time of the amputees' unaffected-arm were significantly related to stroke frequency (r = -.93; p < .01). At 400 m pace, Recovery time accounted for 87% of the variance in stroke frequency, whereas Glide time accounted for 10%. For the amputees' affected-arm, Glide time was significantly related to stroke frequency (r = -.82; p < .01). For this arm, the predictors of Glide, Push and Recovery time accounted for all of the variance in stroke frequency. Glide time had the largest influence, accounting for 68% of the variance, followed by Recovery time (30%) and Push time (2%).

At 400 m pace, the relationships between stroke length and hand pull length (r = .60) and between stroke length and elbow pull length (r = -.45) were moderate. Similarly, the relationships between stroke length and hand slippage (r = -.63) and between stroke length and elbow slippage (r = -.60) were also moderate. At 400 m pace, hand slippage was significantly related to peak backward hand velocity attained during the Insweep (r = .72; p < .05). Elbow slippage was significantly related to peak backward elbow velocity (r = .69; p < .05).

6.5 Discussion

The primary aim of this study was to determine whether the upper extremity kinematics of competitive unilateral arm amputee front crawl swimmers differed between sprint- and distance-paced swimming. The secondary aim was to examine the inter-relationships between selected upper extremity kinematics and swimming performance.

6.5.1 Amputee versus able-bodied front crawl swimmers

The amputees in this study swam faster at their 50 m pace than at their 400 m pace due mainly to an increased stroke frequency. The increase in stroke frequency coincided with a decrease in stroke length. At 50 m pace, the swimming speed (1.32

$m \cdot s^{-1}$), stroke frequency (0.80 Hz) and stroke length (1.67 m) were comparable to those reported by Osborough et al. (2009) for thirteen single-arm amputees, swimming front crawl at maximum speed (speed: 1.36 $m \cdot s^{-1}$; stroke frequency: 0.80 Hz; stroke length: 1.66 m). In this study, the swimming speed (1.19 $m \cdot s^{-1}$), stroke frequency (0.69 Hz) and stroke length (1.74 m) at 400 m pace corresponded to those reported by Osborough et al. (2009) at 87% of maximum speed (speed: 1.19 $m \cdot s^{-1}$; stroke frequency: 0.69 Hz; stroke length: 1.75 m). The mean swimming speed in this study (1.26 $m \cdot s^{-1}$) was much lower than that reported in similar studies for male able-bodied front crawl swimmers (Payton et al., 1999: 1.52 $m \cdot s^{-1}$; McCabe et al., 2011: 1.81 $m \cdot s^{-1}$), but comparable to that for male triathletes, swimming at 1500 m pace (Perrier & Monteil, 2004: 1.24 $m \cdot s^{-1}$).

An increase in swimming speed, from 400 m to 50 m pace, did not bring about a change in the spatial or temporal features of the amputees' hand movement. The amputees' hand followed an identical S-shaped movement trajectory throughout the stroke cycle, under both conditions. At both 50 m and 400 m pace, the amputees' unaffected-arm spent 56% of the total stroke duration in the Recovery and Glide phases, compared to 44% in the Downsweep, Insweep and Upsweep phases. The timing and trajectory of the amputees' unaffected-hand movement was consistently maintained, despite a change in swimming speed.

The amputees' mean (of both paces) absolute hand pull length was much less (0.41 ± 0.06 m vs. 0.60 ± 0.06 m) than that reported by Payton and Lauder (1995) for able-bodied swimmers. Less backward movement of the hand relative to the water indicated less hand slippage. As the amputee swimmers were swimming at a lower speed than the able-bodied swimmers in the Payton and Lauder (1995) study, it is likely that they would have experienced less drag forces acting on their body. Therefore, it would have been easier for the amputees to avoid slippage, compared to their faster able-bodied counterparts.

The relative hand pull lengths indicated that the amputee swimmers maintained the same range of superior-inferior hand motion at 50 m and 400 m pace. In comparison to able-bodied swimmers, the amputees' mean relative hand pull length was considerably less (1.04 ± 0.07 m vs. 1.49 ± 0.12 m) than that reported by Payton and Lauder (1995). This difference could be explained by the relatively small stature of the amputee swimmers and the possibility that not all of the amputees extended their unaffected-elbow fully at the start and end of the underwater stroke. From a visual inspection of the video recordings, certain amputees did not fully reach forward with their hand during the Glide nor fully push their hand back during the Upsweep.

The amputees' mean hand depth (0.59 ± 0.07 m) was shallower than that generally reported for able-bodied front crawl swimmers. For example, McCabe et al. (2011), Payton and Lauder (1995), Payton et al. (1999), Perrier and Monteil (2004) and Scheihauf et al. (1988) reported hand depths ranging between 0.66 ± 0.05 m and 0.77 ± 0.03 m. The difference between the hand depth values in this study and those for able-bodied swimmers might be explained by the amputees using different amounts of body roll and shoulder and elbow flexion/extension compared to their able-bodied counterparts. The differences could further be attributed to the way in which hand depth was quantified. In the present study, the hand mass centre location was used to determine hand depth, whereas McCabe et al. (2011) and Scheihauf et al. (1988) used the swimmer's finger-tip. In the studies by Payton and Lauder (1995), Payton et al. (1999) and Perrier and Monteil (2004) it is unclear whether the authors used the swimmer's finger-tip or hand mass centre to describe hand displacement.

In the present study, the amputees had less medial hand movement during the Insweep phase, than that reported for able-bodied front crawl swimmers. The amputees' mean hand width (0.17 ± 0.06 m) was considerably less than that reported by McCabe et al. (2011), Payton and Lauder (1995), Payton et al. (1999), Perrier and Monteil

(2004) and Scheihauf et al. (1988) for able-bodied swimmers. These authors reported hand width values ranging between 0.27 ± 0.09 m and 0.39 ± 0.07 m. The difference in hand width values between the amputees in this study and able-bodied swimmers, could be accounted for by the amputees rolling less toward their unaffected-side, having less horizontal shoulder flexion and flexing their elbow less during the Insweep, than able-bodied front crawl swimmers.

The amputees in this study flexed their elbow through 34 ± 10° during the Insweep phase. In comparison, McCabe et al. (2011), Payton and Lauder (1995) and Payton et al. (1999) reported that able-bodied swimmers flexed their elbow through 48 ± 9°, 41 ± 14°, and 45 ± 10°, respectively. At the start of the Insweep, the amputees had less elbow extension (148 ± 17°) when compared to their able-bodied counterparts (e.g., 159 ± 17°; Payton et al., 1999). At the end of the Insweep, the amputees exhibited a similar amount of elbow flexion compared to that reported by Payton et al. (1999) for able-bodied swimmers (114 ± 15° vs. 113 ± 6°, respectively).

Not only did the amputees flex their elbow less than able-bodied swimmers, they also exhibited less horizontal shoulder flexion and less shoulder roll during the Insweep phase. During the Insweep, the amputees horizontally flexed their shoulder through 26 ± 14° (from 124 ± 14° to 150 ± 12°); whereas able-bodied swimmers have been reported (Payton et al., 1999) to horizontally flex theirs through 41 ± 13° (from 100 ± 10° to 141 ± 15°). During the same phase, the amputees rolled their shoulders through 17 ± 8° (from 29 ± 6° to 13 ± 10°) towards a neutral position. In comparison, able-bodied swimmers have been reported by Payton et al. (1999) to roll through 36 ± 7° during breath-holding front crawl (from 55 ± 4° to 19 ± 11°).

In able-bodied front crawl, as one arm travels through the Insweep phase the opposite arm is recovered over the water, typically using a “high-elbow” technique. In order to execute this technique swimmers have to roll their shoulders sufficiently far enough to ensure that the recovering hand is not dragged through the water. In the present study, the arm amputees recovered their affected-arm only 0.14 m above the water. As a consequence, when recovering their affected-arm they did not need to roll their shoulders to the same extent as their able-bodied counterparts. As the insweep of the hand has been identified as a mechanism that can assist the rolling of a swimmer back towards the neutral position during the opposite arm's recovery (Payton et al., 1999), this might explain why the amputees in this study used less elbow flexion and less horizontal shoulder flexion, and consequently exhibited a lower peak inward hand velocity and a smaller medial hand insweep, when compared to able-bodied swimmers. Less torque about the amputees' long axis was required, during this phase, to roll the body back toward the neutral position, compared to able-bodied front crawl swimmers.

Not only are pronounced medio-lateral hand movements employed by skilled able-bodied swimmers to utilise hydrodynamic forces to help control body roll (Payton et al. 2002), these movements generate propulsion (Payton & Lauder, 1995). As a consequence of less elbow flexion and horizontal shoulder flexion, it might be expected that the amputees' ability to generate high propulsive forces using their hand insweep was compromised. During the Insweep phase at 50 m pace, the amputees' peak inward hand velocity was 48% lower (1.09 ± 0.31 $m \cdot s^{-1}$) than that reported by Payton and Lauder (1995) for able-bodied front crawl swimmers (2.09 ± 0.39 $m \cdot s^{-1}$). Since hand velocity during the Insweep is produced in part by elbow flexion and horizontal shoulder flexion, and the velocity at which the hand moves relative to the water is important for successfully generating propulsion (Payton et al., 2002), the lower inward hand velocity of the amputees might suggest that the propulsion generated from the amputees' hand insweep would be less, compared to able-bodied swimmers. It might be that unilateral arm amputee front crawl rely more on backward hand velocity rather than medial hand velocity to generate propulsion. However, since the angle of attack and sweep back angle of the amputees' hand was not determined in the current study, propulsive forces were not calculated.

Interestingly, the amputees' peak backward hand velocity during the Insweep phase, at 50 m pace, was only 10% less (1.35 ± 0.27 $m \cdot s^{-1}$) than that reported by Payton and Lauder (1995) for able-bodied front crawl swimmers (1.50 ± 0.47 $m \cdot s^{-1}$). Furthermore, the amputees generated significantly less peak backward hand velocity during this phase, when swimming at 400 m pace compared to 50 m pace. This was probably because there was less need for the amputees to emphasise the propulsive backward push to progress through the water, when swimming at 400 m pace.

6.5.2 Amputees' affected-arm versus unaffected-arm

The relative duration of certain affected- and unaffected-arm stroke phases differed between the sprint- and distance-paced swimming trials. At 400 m pace, the amputees had a longer relative Glide phase and a shorter relative Recovery phase for both arms, than at 50 m pace. At 50 m pace, percentage Pull time for the unaffected-arm was greater than at 400 m pace, while for the affected-arm it remained unchanged. At 50 m pace, relative Push phase duration for the unaffected-arm was less than at 400m pace. Conversely for the affected-arm, at 50 m pace, relative Push phase duration was greater than at 400 m pace.

With the exception of the relative Recovery phase duration, the percentage phase times showed an identical trend to that of the absolute phase times. Percentage Recovery time was shorter at 400 m than at 50 m pace for both arms; in absolute terms the opposite was true. The actual Recovery time was longer at 400 m pace than at 50 m pace (unaffected-arm: 0.65 ± 0.12 s at 400 m pace and 0.59 ± 0.09 s at 50 m pace; affected-arm: 0.65 ± 0.11 s at 400 m pace and 0.59 ± 0.09 s at 50 m pace). The longer absolute Recovery time at 400 m pace could partially explain the lower stroke frequency at this pace, compared to that observed at 50 m pace.

The mean relative durations of the amputees' arm stroke phases were 36%, 9%, 10% and 45% for the Glide, Pull, Push and Recovery, respectively. In comparison, McCabe et al. (2011) reported mean values of 31%; 16%; 18% and 29% for the corresponding phases in fifteen male able-bodied front crawl swimmers. These differences could be accounted for by gender differences between the two populations and the way in which the stroke phases were defined. In the current study, elbow position was used to identify the four arm phases, whereas McCabe et al. (2011) used hand position to do this. Even with this difference however, the values reported by McCabe et al. (2011) did not account for 100% of the stroke time duration. In their study, 6% of the total stroke time duration was unaccounted for.

Peak elbow velocities for the affected- and unaffected-arm did not differ between 50 m and 400 m pace, with the exception of the peak downward elbow velocity during the Pull phase. During the underwater stroke, the amputees' affected-arm had peak downward and peak backward elbow velocities that were three times greater than that of their unaffected-arm. The difference in peak elbow velocity between the affected- and unaffected-arm could be attributed to the physical impairment of the amputees.

Being deprived of an important propelling surface (hand plus forearm segment), competitive unilateral arm amputee swimmers must rely on the surface area of the remaining limb (upper-arm) to generate propulsion. Since the hydrodynamic force generated by the limb is proportional to its surface area and the square of its velocity relative to the water (Toussaint & Beek, 1992), the decreased surface area of the amputees' affected-arm would result in an increased limb velocity, for a given muscular force. Thus, unlike the unaffected-arm where the hand and forearm segment had purchase on and pushed against the water to propel the swimmer forward, the affected-arm was pulled through the water at high velocity. Pulling the affected-arm through the water at high velocity may have occurred as a consequence of reduced drag, or might be a conscious choice made by the amputees in an attempt to generate propulsion. As there exists, for any given swimming speed, a minimum angular velocity at which the upper-arm must be rotated to generate effective propulsion (Lecrivain et al., 2010), single-arm amputees need to pull their affected-arm through the water very fast if there is any hope of generating propulsion from it. Further work is needed to verify whether the affected-arm of a unilateral arm amputee swimmer can contribute effectively to propulsion during high speed, full stroke front crawl swimming.

The unilateral arm amputee swimmers exhibited asymmetrical timings of their affected- and unaffected-arm strokes. In general, it was apparent that the amputees held their affected-arm stationary in the Glide phase before pulling it rapidly downward and backward. As the affected-arm was then pushed backward and upward towards the hip, its motion slowed. Conversely, the amputees' unaffected-arm was pulled steadily downward and backward before being rapidly pushed upward. It is likely that this final backward and upward push of the unaffected-arm during the underwater stroke is a key feature of single-arm amputee front crawl. It is here that the highest propulsive forces are generated by able-bodied swimmers (Maglischo et al., 1988; Schleihauf et al., 1988). Further work is needed to examine the relationship between arm velocity and the application of propulsive force, during the different stoke phases in unilateral arm amputee front crawl swimming. Additional work might also consider the role played by the affected- and unaffected-arm arm to streamline the body and minimise active drag, during the different stroke phases.

The amputees' affected- and unaffected-arm trajectories did not differ between 50 m and 400 m pace. The amputee swimmers pulled their affected-arm through the water differently to the upper-arm segment of their unaffected-arm. The depth that the amputees' affected-elbow reached, during the underwater stroke, was significantly deeper (0.42 ± 0.05 m) than that reached by their unaffected-elbow (0.34 ± 0.06 m). This could be accounted for by the amputees using a "high-elbow" technique when pulling their unaffected-arm through the water and by rolling less to the unaffected-side. The backward travel of the amputees' affected-elbow, relative to the water, was significantly more (0.24 ± 0.04 m) than that of their unaffected-elbow (0.10 ± 0.05 m) even though the relative elbow pull length was similar for both arms. This difference could be accounted for by the higher backward velocity of the affected-arm's elbow, compared to the elbow on the unaffected-arm.

Within the group, the amputee swimmers conformed to one of three distinct movement patterns when pulling their affected-arm through the water. When viewed from the front, swimmers pulled their affected-arm through the water: (1) in a wide arc outside the shoulder-line (n = 4). For these swimmers the mean upper-arm angle at the deepest position was 55 ± 7° at 50 m pace and 61 ± 6° at 400 m pace; (2) underneath and in-line with the shoulder (n = 4). The mean upper-arm angle, at the same position, for these swimmers was 85 ± 3° at 50 m pace and 88 ± 5°at 400 m pace; and (3) in a narrow arc inside the shoulder-line (n = 2). These swimmers had a mean upper-arm angle at the deepest position of 105 ± 4° at 50 m pace and 122 ± 0° at 400 m pace. Although a variety of different underwater arm trajectories have been observed in previous unilateral arm amputee studies (e.g., Osborough et al., 2009; Payton & Wilcox, 2006), this is the first time that they have been described fully and accurately using three-dimensional analysis techniques. However, as propulsion was not quantified in this study, it is unclear whether some of these trajectories resulted in more effective stroking technique and ultimately more successful performance, than others.

Shoulder roll did not differ between sprint- and distance-pace swimming, but was asymmetrical between the affected- and unaffected-side of the amputee swimmers. Not only did the amputees roll more to the affected-side of the body than to the unaffected-side (43 ± 8° vs. 33 ± 7°), but the instant at which these maxima occurred during the corresponding arm stroke cycle differed. The shoulders reached maximum roll and commenced rolling back towards the neutral at the end of the Glide phase on the unaffected-side and during the Push phase on the affected-side.

In able-bodied front crawl, the dominant mechanism for generating body roll is buoyant force (Yanai, 2004). When the amputees' affected-arm was recovered over the water (Figure 6.5) a clockwise torque acting about the swimmers' long axis would have been created. This clockwise torque would have been substantially lower than the anti-clockwise torque created when the unaffected-arm was recovered over the water. As this cannot explain the greater shoulder roll that occurred when the unaffected-arm was recovered over the water, the amputees must have utilised mechanisms other than the buoyant torque, such as the external torques from non-propulsive fluid forces (Yanai, 2003) and internal reaction torques resulting from limb accelerations (Payton et al., 2002), to control their body roll.

6.5.3 Inter-swimmer correlations for the amputees

At both 50 m and 400 m pace, the significant correlation between swimming speed and stroke frequency indicates that the faster swimmers used higher stroke frequencies, compared to their slower counterparts. There was a moderate negative inter-swimmer correlation between swimming speed and stroke length. These findings agree with those of Osborough et al. (2009) and Payton and Wilcox (2006), in that the fastest amputees were able to attain the highest swimming speed by having the highest stroke frequency, rather than swimming with the longest possible stroke length. At both 50 m and 400 m pace, stroke frequency was more important than stroke length in influencing short-term swimming performance.

Under both conditions, there were significant negative correlations between stroke frequency and the relative duration of certain affected- and unaffected-arm stroke phases. The fastest amputees' unaffected-arm spent less time in the Glide and Recovery phases, while their affected-arm spent less time in the Glide and Push phases, when compared to the slower swimmers. For able-bodied swimmers (Chollet et al., 2000) and unilateral arm amputees (Osborough et al., 2010) higher stroke frequencies were significantly related to shorter Glide phase durations. In this regard, the faster amputees in this study exhibited similar characteristics to those of other swimmers, when compared to their slower counterparts. By reducing the time spent in the Glide and Recovery phases, the fastest swimmers were able to attain the highest stroke frequencies.

Although there was a moderate negative inter-swimmer correlation between swimming speed and stroke length under both conditions, the importance of stroke length should not be completely ignored. Any improvements in a swimmer's technical performance over a long-term period would be reflected in their ability to swim at a given speed with a longer stroke length. At 50 m pace, the relationship between stroke length and hand pull length was positive and significant. A similar, but non-significant trend was evident at 400 m pace. Since hand pull length only showed a low and non-significant relationship with total arm length, those amputees who swam with the longest strokes did so by fully reaching forward with their hand during the Glide and fully pushing their hand back during the Upsweep.

Not only is a swimmer's stroke length influenced by the length of an individual's arm pull, it is also influenced by slippage. At 50 m pace, there were significant negative correlations between stroke length and hand slippage and between stroke length and elbow slippage. Those amputees who swam with the longest strokes were able to minimise arm slippage, compared to those who had the shortest strokes. A similar, but non-significant trend was evident at 400 m pace. Under both conditions, slippage of the hand was significantly related to the peak backward hand velocity attained during the Insweep. Similarly, the relationship between elbow slippage and peak backward elbow velocity was positive and significant, at both 50 m and 400 m pace. The amputee swimmers who had the longest strokes, had the least amount of arm slippage and exhibited the lowest backward arm velocities, relative to the water, during the middle part of the underwater stroke

6.6 Summary and Conclusion

The results from this study show that only a few upper extremity limb kinematics differed between sprint- and distance-pace. These included: peak backward hand velocity, peak downward elbow velocity, for the affected-arm, and certain arm stroke phase durations. Upper extremity kinematics differed between the affected- and unaffected-side of the body. The amputees' hand followed a more linear underwater trajectory, when compared to the hand paths of able-bodied swimmers. During the Insweep of the unaffected-arm, the amputees flexed their elbow less and exhibited less horizontal shoulder flexion and less shoulder roll than that exhibited by able-bodied swimmers. During the same phase, the amputees' inward hand velocity was much lower than that of able-bodied swimmers. These findings imply that single-arm amputee front crawl swimmers do not use pronounced medial hand movements during their Insweep. This may be due to swimmers needing less medially directed hydrodynamic force to control body roll or them relying more on a backward hand movement to generate propulsion. The amputees pulled their affected-arm through the water differently to the upper-arm segment of their unaffected-arm. When viewed from the front, swimmers pulled their affected-arm through the water: (1) in a wide arc outside the shoulder-line (n = 4); (2) underneath and in-line with the shoulder (n = 4); or (3) in a narrow arc inside the shoulder-line (n = 2). The amputees used more shoulder roll during the recovery of their unaffected-arm than during the affected-arm recovery. Certain selected upper extremity kinematics were related to stroke length and stroke frequency. Although there was a moderate negative correlation between swimming speed and stroke length, swimmers who had the longest strokes had the least amount of arm slippage and exhibited the lowest backward arm velocities, relative to the water, during the middle part of the underwater stroke.

CHAPTER SEVEN

INTRA-CYCLIC VELOCITY FLUCTUATIONS AT SPRINT AND DISTANCE PACE

This chapter examines how the amputees' mass centre velocity fluctuates during the underwater pull of the affected- and unaffected-arm, at 50 m and 400 m pace. The chapter discusses the link between the fluctuations in mass centre velocity and the changes in backward velocity of the arms' most distal point (i.e. stump tip and finger tip). Chapter 7 relates to academic aim 5, in Section 2.13.

7.1 Abstract

The primary aim of this study was to establish whether the intra-cyclic velocity fluctuations of competitive unilateral arm amputee front crawl swimmers differed between sprint- and distance-paced swimming. The secondary aim was to determine the influence of the backward velocity of the arms' most distal point on intra-cyclic swimming velocity, at both paces. A three-dimensional analysis was conducted on ten highly-trained swimmers with a single-arm amputation. The amputees' mean intra-cyclic velocity fluctuation (± 15%) did not differ between sprint- and distance-paced swimming. The amputees were effective at increasing their swimming velocity with their unaffected-arm, but not so with their affected-arm. The amputees' intra-cyclic swimming velocity increased significantly during the unaffected-arm's underwater stroke, concomitant with a significant increase in the backward velocity of the hand. In contrast, when pulling their affected-arm through the water, the amputees experienced a significant reduction in their swimming velocity, despite the significant increase in the backward velocity of the stump. These findings imply that unilateral arm amputee front crawl swimmers: (1) need to execute the final backward push of their hand at high velocity to successfully generate propulsion; and (2) may not be able to generate effective propulsion with their affected-arm at swimming velocities above 1.2 $m \cdot s^{-1}$.

7.2 Introduction

Front crawl swimming technique consists of an alternating right and left arm stroke and a varying number of alternating kicks. Whilst underwater, a swimmer's hand is pulled through a series of non-propulsive and propulsive phases as it follows an S-shaped pull pattern (Maglischo et al., 1988; Scheihauf et al., 1988) and the legs kick, typically with a six-beat rhythm (Sanders & Psycharakis, 2009; Yanai, 2003). Throughout the stroke cycle, swimmers maintain horizontal alignment while rolling about their long axis to either side, which is coordinated with the alternating action of the arms. To swim effectively, individuals must coordinate these complex body movements to maximise propulsion and minimise resistance.

When considering the effectiveness of a swimmer's technique, an understanding of the interplay between propulsion and resistance is crucial. In front crawl, a swimmer's hand and corresponding forearm generate the majority of propulsion (Deschodt et al., 1999; Toussaint & Beek, 1992). Such propulsion is related to the velocity at which the swimmer's hand and forearm segments move relative to the water (Payton & Lauder, 1995; Payton et al., 2002). Resistance, which hinders a swimmer's progression through the water, is related to the size, shape and velocity of the swimmer (Toussaint & Truijens, 2005). With the constantly changing position and orientation of a swimmer's limbs within the front crawl stroke cycle, both propulsion and resistance will fluctuate. Consequently, the swimmer's horizontal velocity will fluctuate throughout the stroke cycle.

The horizontal intra-cyclic velocity fluctuations of a swimmer have been determined using different approaches. In many front crawl studies (Alberty et al., 2005; Craig & Pendergast, 1979; Payton & Wilcox, 2006; Schnitzler et al., 2010), a purpose-built device, attached to a fixed point on a swimmer's body, via a wire was used. Although such devices are time and cost efficient and measure swimming velocity directly, they are limited. A fixed point such as the hip does not represent accurately the kinematics of a swimmer's mass centre (Barbosa et al., 2005; Psycharakis & Sanders, 2009) and the vertical movements of a fixed point might be misinterpreted by purpose-built wire devices as forward displacements (Craig & Pendergast, 1979). Given these limitations, and the fact that swimming involves three-dimensional movements, three-dimensional analysis techniques must be used to accurately determine the exact motion of a swimmer's mass centre. Only Psycharakis and Sanders (2009) and Psycharakis et al. (2010) appear to have used three-dimensional motion analysis to determine the intra-cyclic velocity fluctuations of able-bodied front crawl swimmers.

Front crawl swimmers with a single-arm amputation, show adapted variations in their arm stroke technique to compensate for their missing limb. Single-arm amputees have significantly more catch-up coordination of their affected-arm compared to their unaffected-arm (Osborough et al., 2009) and pull their affected-arm though the water much faster than their unaffected-arm (Chapter 6, Study 4). When swimming slowly (1.0 $m \cdot s^{-1}$), single-arm amputees are able to use their affected-arm to generate propulsion (Lecrivain et al., 2008) and, at 1.09 $m \cdot s^{-1}$, increase their intra-cyclic swimming velocity (Payton & Wilcox, 2006). However, as a unilateral arm amputee swims faster (up to 1.2 $m \cdot s^{-1}$), their ability to generate effective propulsion with their affected-arm decreases (Lecrivain et al., 2010). Since there exists, for any given swimming pace, a minimum angular velocity at which the affected-arm must be rotated to generate effective propulsion, at swimming velocities greater than 1.2 $m \cdot s^{-1}$, amputee swimmers might not be able to rotate their affected-arm fast enough to generate effective propulsion. If so, it might be expected that intra-cyclic velocity fluctuations of single-arm amputees would increase with an increase in swimming pace. Furthermore, with an increase in swimming pace, it would be expected that there would be a decrease in the intra-cyclic swimming velocity during the underwater pull of the amputees' affected-arm, due to its reduced ability to generate effective propulsion. Such predictions however, are primarily based on results from theoretical models, using computational fluid dynamics, of one female, below-elbow amputee swimmer (Lecrivain et al., 2008; 2010). There is a need therefore to experimentally validate the theoretical findings from these models for a group of unilateral arm amputees, at swimming speeds typically exhibited during competition.

The primary aim of this study was to establish whether the intra-cyclic velocity fluctuations of competitive unilateral arm amputee front crawl swimmers differed between sprint- and distance-paced swimming. The secondary aim was to determine the influence of the backward velocity of the arms' most distal point on intra-cyclic swimming velocity, at both paces. The hypotheses for this study were: (1) intra-cyclic velocity fluctuations would differ between the two swimming paces; and (2) intra-cyclic swimming velocity would decrease during the affected-arm's underwater stroke and increase during the unaffected-arm's underwater stroke.

7.3 Methods

7.3.1 Participants

Ten (2 male and 8 female) competitive swimmers (age 16.8 ± 3.3 yrs; height 1.68 ± 0.09 m; mass 63.9 ± 14.2 kg), whose mean long course 50 m front crawl personal best time was 33.1 ± 3.1 seconds, participated in this study. All the participants were single-arm amputees, at the level of the elbow and were the same as those who participated in Study 4 (Chapter 6). Further details of the participant group can be found in Section 6.3.1. The procedure for the data collection was approved by the Institutional Ethics Committee. All participants provided either written informed consent or, in the case of minors, parental written consent before taking part in the study.

7.3.2 Data Collection and Data Processing

The data collection and data processing procedures used in this study are the same as those used in Study 4 (Chapter 6). Full details of the data collection and processing procedures can be found in Sections 6.3.2 and 6.3.3, respectively. Only the essential details are reported here.

After a standardised 600 m warm up, participants were randomly allocated into one of two test groups. Each participant completed two 25 m front crawl trials, from a push start, at intervals of 3 minutes. One of these trials was performed at 50 m swimming pace and the other was performed at 400 m swimming pace. Each participant's trial though a calibrated performance volume (6.75 m^3) was recorded with six stationary and synchronised 50 Hz cameras. Four cameras were below and two were above the water.

A participant's full stroke cycle from within the performance volume, at 50 m and 400 m swimming pace, was used for analysis. For each separate camera view, the estimated locations of eighteen body landmarks were manually digitised, at 50 Hz, using SIMI Motion 7.2. These points defined a thirteen-segment model of the body. Image coordinates were transformed into three-dimensional object-space coordinates using a DLT algorithm. The calculated three-dimensional coordinates were then smoothed using a 2^{nd} order low pass Butterworth filter at a cut-off frequency of 6-8 Hz.

7.3.3 Body Segment Parameter Calculations

Accurate body segment parameter (BSP) data for individual participants were obtained with the use of the elliptical zone method of Jenson (1976) applied using the "eZone" software programme developed by Deffeyes and Sanders (2005). The procedure to calculate the participants' BSP data was the same as that used in Study 4 (Chapter 6). Full details of the BSP calculations can be found in Section 6.3.4.

7.3.4 Definition of Variables

The stroke cycle of both arms was divided into four phases (Chollet et al., 2000; McCabe et al., 2011). For the unaffected-arm, the stroke cycle was from finger entry to next finger entry. For the affected-arm it was from elbow entry to next elbow entry.

(A) *Glide*: from where the finger/elbow entered the water to where it began moving backward relative to the water.

(B) *Pull*: from the end of the Glide to where the finger/elbow was vertically aligned with the shoulder joint centre.

(C) *Push*: From the end of the Pull to where the finger/elbow ended its backward movement relative to the water.

(D) *Recovery*: from the end of the Push to next finger/elbow entry.

The following variables were obtained from the video recordings, at each participant's 50 m and 400 m swimming pace: 1) *Swimming velocity* ($m{\cdot}s^{-1}$): mean forward velocity of the participant's mass centre during one stroke cycle; 2) *Maximum velocity* ($m{\cdot}s^{-1}$): peak forward velocity of the participant's mass centre during the affected- and unaffected-arm's respective underwater phases; 3) *Minimum velocity* ($m{\cdot}s^{-1}$): lowest forward velocity of the participant's mass centre during the affected- and unaffected-arm's respective underwater phases; 4) *Velocity fluctuation* (%): difference between the maximum and minimum velocities within a stroke cycle, expressed as a percentage of the mean swimming velocity; 5) *Relative maximum velocity* (%): maximum velocity expressed as a percentage of the mean swimming velocity; 6) *Relative minimum velocity* (%): minimum velocity expressed as a percentage of the mean swimming velocity; 7) *Peak arm extension velocity ($rad{\cdot}s^{-1}$)*: maximum angular velocity of the upper-arm whilst underwater, about the horizontal (*X*-axis), when projected onto the *X*-*Z* plane ; 8) *Segment pull velocity ($m{\cdot}s^{-1}$)*: mean backward velocity of the most distal point on the arm (i.e. stump-tip and finger-tip) during the Pull phase;

9) *Segment push velocity ($m \cdot s^{-1}$)*: mean backward velocity of the most distal point on the arm (i.e. stump tip and finger tip) during the Push phase.

7.3.5 Statistical Analyses

Means and standard deviations were computed for all the measured variables. Normal distribution of the data was verified using the Shapiro-Wilks test. Eight multivariate general linear modeling (GLM) tests were used to compare changes in the measured variables between the 50 m and 400 m pace and between the affected- and unaffected-arm. Two separate multivariate GLM tests were used to compare changes in mass centre velocity between the end of the Glide, Pull and Push phases and between the 50 m and 400 m pace, for the affected- and unaffected-arm. Two further multivariate GLM tests were used to compare changes in segment velocity between the Pull and Push phases and between 50 m and 400 m pace, for the affected- and unaffected-arm. Multiple comparisons were made with the Bonferroni *post hoc* test. In all comparisons, the level of significance was set at $p < .05$. Statistical analysis procedures were performed using SPSS 18.0 software.

The assessment of intra- and inter-tester reliability of the digitising process was outlined in Study 4 (Chapter 6). Further details can be found in Section 6.3.6. As the digitised data in Chapter 6 was determined to be both reliable and objective, it was assumed that the digitised data in current study was also reliable and objective.

7.4 Results

The participants' intra-cyclic velocity fluctuations are presented in Figure 7.1. At 50 m pace (1.32 ± 0.14 $m \cdot s^{-1}$), intra-cyclic velocity fluctuations ranged between ± 10.0% (Swimmer ♀ 5) and ± 19.5% (Swimmer ♀ 1). At 400 m pace (1.19 ± 0.11 $m \cdot s^{-1}$), intra-cyclic velocity fluctuations ranged between ± 10.5% (Swimmer ♂ 2) and ± 24.0% (Swimmer ♀ 6).

As a group, intra-cyclic velocity fluctuations did not differ significantly between sprint- and distance-pace. Although not significant, the mean velocity fluctuation during the underwater stroke of the unaffected-arm was less at 50 m pace than at 400 m pace (± 17.1% vs. ± 19.5%). On the affected-side, mean velocity fluctuation was greater at 50 m pace compared to 400 m pace (± 13.3% vs. ± 11.0%). At both 50 m and 400 m pace, mean intra-cyclic velocity fluctuation on the unaffected-side was greater than on the affected-side. This difference was significant at 400 m pace (unaffected-side: ± 19.5% vs. affected-side: ± 11.0%; $p < .01$) but not at 50 m pace.

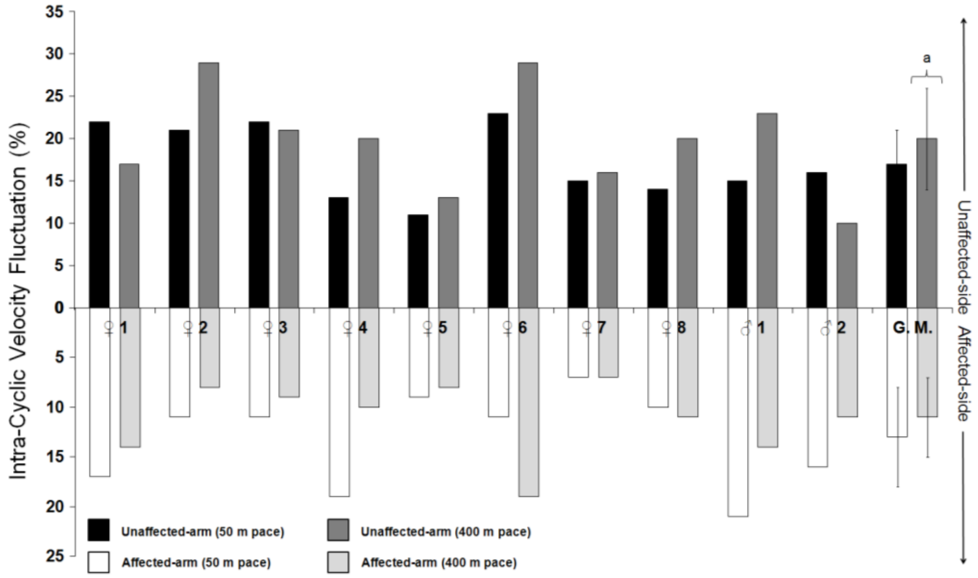

Figure 7.1. Intra-cyclic velocity fluctuations, as a percentage of mean swimming velocity, for eight female (♀) and two male (♂) arm amputee front crawl swimmers swimming at 50 m and 400 m pace. G.M. = Group Mean (± SD).

[a] Denotes significant difference ($p < .01$) between affected- and unaffected-side.

Table 7.1 shows means and standard deviations of the measured variables for the affected- and unaffected-arm, at 50 m and 400 m pace. The maximum and minimum values of the mass centre velocity were significantly higher ($p < .01$) at 50 m pace compared to 400 m pace. However, when expressed relative to the mean swimming velocity, no significant differences were found for the relative maximum and minimum velocity values, between conditions. Peak arm extension velocity was significantly higher ($p < .01$) at 50 m pace for both the affected- and unaffected-arm, compared to at 400 m pace. The backward velocity of the stump-tip during the Pull phase was significantly greater ($p < .01$) at 50 m pace than at 400 m pace. For most of the measured variables there were significant differences between the affected- and unaffected-arm. Those that didn't show a significant inter-arm difference were minimum mass centre velocity (absolute and relative) and segment push velocity.

Table 7.1. Means (M) and standard deviations (SD) of the measured variables for the unaffected- and affected-arm, at 50 m and 400 m pace.

	Unaffected-arm				**Affected-arm**			
	50 m pace		**400 m pace**		**50 m pace**		**400 m pace**	
	M	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***
Min. Vel. ($m \cdot s^{-1}$)	1.23	0.15 ^{a}	1.07	0.08	1.19	0.13 ^{a}	1.07	0.10
Max. Vel. ($m \cdot s^{-1}$)	1.45	0.14 $^{a, b}$	1.30	0.11 ^{b}	1.36	0.17 ^{a}	1.20	0.11
Vel. Fluctuation (%)	17.1	4.3	19.5	6.3 ^{b}	13.3	4.7	11.0	3.8
Min. Vel. (%)	93.0	2.6	90.0	4.1	90.3	5.7	90.5	5.6
Max. Vel. (%)	110	2.7 ^{b}	110	5.8 ^{b}	104	6.6	101	6.4
Ext. Vel ($rad \cdot s^{-1}$)	7.02	0.81 $^{a, b}$	6.25	0.90 ^{b}	9.88	1.37 ^{a}	9.04	1.56
Seg. Pull Vel. ($m \cdot s^{-1}$)	0.58	0.19	0.55	0.11 ^{b}	0.94	0.21 ^{a}	0.75	0.23
Seg. Push Vel. ($m \cdot s^{-1}$)	1.04	0.17	0.97	0.16	1.10	0.32	0.99	0.16

^{a} Denotes significant difference ($p < .01$) between 50 m and 400 m pace.

^{b} Denotes significant difference ($p < .01$) between affected- and unaffected-arm.

Figure 7.2 shows the mass centre velocity, expressed relative to the mean swimming velocity, at the end of the Glide, Pull and Push phases of the affected- and unaffected-arm, at 50 m and 400 m pace. From the start of the unaffected-arm's Pull to the end of its Push phase, mass centre velocity increased significantly ($p < .01$). In contrast, mass centre velocity decreased significantly ($p < .01$) during the corresponding phases of the affected-arm. When expressed as a percentage of mean swimming velocity, mass centre velocity increased from 96.4 ± 4.7% at the end of the Glide, to 95.8 ± 4.3% at the end of the Pull, to 104.8 ± 5.5% at the end of the Push for the unaffected-arm. For the affected-arm, mean relative mass centre velocity decreased from 100.9 ± 6.0% at the end of the Glide, to 96.2 ± 5.8% at the end of the Pull, to 96.5 ± 6.7% at the end of the Push.

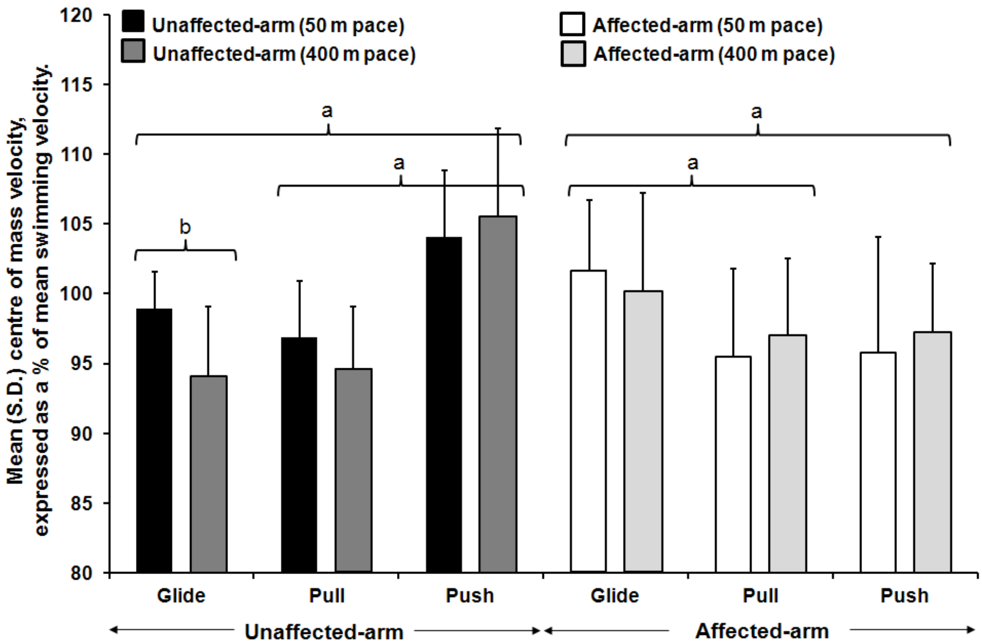

Figure 7.2. Mean (± SD) mass centre velocity, expressed as a percentage of mean swimming velocity at the end of the Glide, Pull and Push phases of the unaffected- and affected-arm at 50 m and 400 m pace.

[a] Denotes significant differences ($p < .01$) between phases.

[b] Denotes significant difference ($p < .05$) between 50 m and 400 m pace.

The mean backward velocities of the finger-tip (unaffected-arm) and the stump-tip (affected-arm) during the Pull and Push phases are shown in Figure 7.3. At 50 m pace, the mean backward velocity of the finger-tip increased significantly ($p < .01$) from 0.58 ± 0.19 m·s^{-1} during the Pull to 1.04 ± 0.17 m·s^{-1} during the Push. At 400 m pace, the increase in finger-tip velocity between the Pull and Push phase also occurred (from 0.55 ± 0.11 m·s^{-1} to 0.97 ± 0.16 m·s^{-1}; $p < .01$). Under both conditions, the mean backward velocity of the stump-tip increased significantly ($p < .01$) from the Pull to the Push phase (at 50 m pace from 0.94 ± 0.21 m·s^{-1} to 1.10 ± 0.16 m·s^{-1}; at 400 m pace from 0.75 ± 0.23 m·s^{-1} to 0.99 ± 0.16 m·s^{-1}). The mean backward velocity of the stump-tip during the Pull was significantly lower at 400 m pace than at 50 m pace.

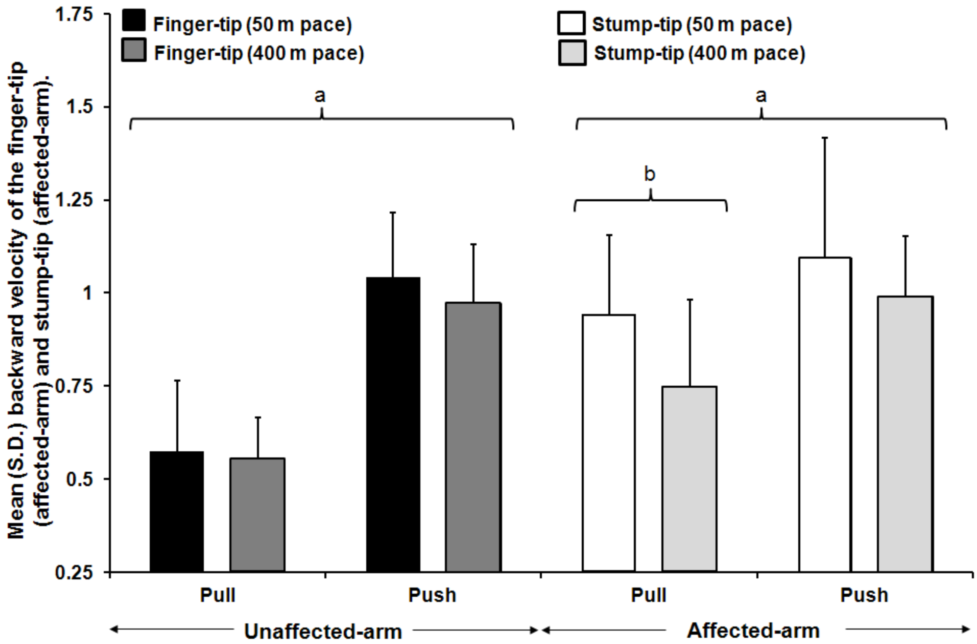

Figure 7.3. Mean (± SD) backward velocity of the finger-tip (unaffected-arm) and stump-tip (affected-arm) during the Pull and Push phases, at 50 m and 400 m pace.

[a] Denotes significant differences ($p < .01$) between phases.

[b] Denotes significant difference ($p < .05$) between 50 m and 400 m pace.

7.5 Discussion

The primary aim of this study was to establish whether the intra-cyclic velocity fluctuations of competitive unilateral arm amputee front crawl swimmers differed between sprint- and distance-paced swimming. The secondary aim was to determine the influence of the backward velocity of the arms' most distal point on intra-cyclic swimming velocity, at both paces. The first hypothesis was rejected: intra-cyclic velocity fluctuations were not different between the two swimming paces. The second hypothesis was accepted: intra-cyclic swimming velocity decreased during the affected-arm's underwater stroke and increased during the unaffected-arm's underwater stroke.

The amputees' mean intra-cyclic velocity fluctuation did not differ between 50 m and 400 m pace. In the current study, the swimmers' velocity fluctuated ± 15% from their mean swimming velocity. This was substantially lower than that generally reported for able-bodied front crawl swimmers. Intra-cyclic velocity fluctuations, of fixed points on the bodies of able-bodied swimmers, have been reported to range between ± 20% and ± 23% (Alberty et al., 2005; Craig & Pendergast, 1979). Using three-dimensional motion analysis, Psycharakis and Sanders (2009) and Psycharakis et al. (2010) reported intra-cyclic velocity fluctuations of ± 22%. Intra-cyclic velocity fluctuations of ± 14% and ± 18% have also been reported for elite and recreational swimmers, respectively (Schnitzler et al., 2010). However, as these authors calculated intra-cyclic velocity fluctuations by determining the coefficient of variation of the swimmer's velocity, this could, in part, explain the lower values, compared to the other front crawl studies.

The amputees in the present study had a slight lower mean intra-cyclic velocity fluctuation than the ± 18% reported for eight (2 male and 6 females) highly-trained unilateral arm amputee swimmers during arms-only front crawl (Payton & Wilcox, 2006). The lower intra-cyclic velocity fluctuation of the amputees in this study could be explained by the way in which instantaneous velocity was quantified, the pace at which the participants swam and the type of front crawl studied. Payton and Wilcox (2006) used a purpose-built device that measured the instantaneous velocity of a fixed point on the swimmers' waist, during arms-only front crawl at a pace of 1.09 ± 0.13 $m \cdot s^{-1}$. In the current study, swimmers performed full stroke front crawl at two paces (1.19 ± 0.11 $m \cdot s^{-1}$and 1.32 ± 0.14 $m \cdot s^{-1}$) with the velocity of their mass centre being determined using three-dimensional motion analysis.

Accounting for the different measurement techniques and swimming paces between the two studies above, it is likely that the use of a leg kick in the present study made a substantial contribution to lowering the intra-cyclic velocity fluctuations, compared to when swimming arms-only. It is probable that the leg kick ensured ongoing propulsion, during the phases when the arm stroke was non-propulsive (Deschodt et al., 1999). When examining each swimmer's intra-cyclic velocity-time curve in the present study, a clear number of maxima were evident which coincided with the execution of the swimmer's leg kicks. The propulsive effect of these kicks would have been to raise the amputees' minimum velocity, thus maintaining a more uniform intra-cyclic swimming velocity, compared to swimming arms-only. By utilising their leg kick, particularly during non-propulsive arm stroke phases, these swimmers might be able to reduce the effect of resistive forces acting on them. However, the relative contribution of the leg kick to swimming performance remains unknown for unilateral arm amputee front crawl swimmers and warrants further study.

The amputee swimmers attained their maximum velocity during the Push phase of their unaffected-arm stroke. During their affected-arm stroke however, maximum velocity occurred early in the Pull phase, while the unaffected-arm was being recovered over the water. The amputees' maximum velocity at 400 m pace was 1.30 ± 0.11 $m \cdot s^{-1}$ during the Push of their unaffected-arm and 1.20 ± 0.11 $m \cdot s^{-1}$ during the Pull phase of their affected-arm. Similar values have been reported for single-arm amputee swimmers during arms-only front crawl. Payton and Wilcox (2006) reported maximum velocities of 1.30 ± 0.17 $m \cdot s^{-1}$ and 1.14 ± 0.11 $m \cdot s^{-1}$ during the unaffected- and affected-arm strokes, respectively.

Unlike the amputees in the Payton and Wilcox (2006) study, the amputees in the present study were unable to increase their swimming velocity using their affected-arm. In this study under both conditions, the maximum velocity during the affected-arm's underwater stroke was similar to the swimmer's mean velocity (at 50 m pace, peak: 1.36 ± 0.17 $m \cdot s^{-1}$, mean: 1.32 ± 0.14 $m \cdot s^{-1}$; at 400 m pace, peak: 1.20 ± 0.11 $m \cdot s^{-1}$, mean: 1.19 ± 0.11 $m \cdot s^{-1}$). In contrast for the unaffected-arm, the maximum velocity was higher than the swimmers' mean velocity (at 50 m pace, peak: 1.45 ± 0.14 $m \cdot s^{-1}$, mean: 1.32 ± 0.14 $m \cdot s^{-1}$; at 400 m pace, peak: 1.30 ± 0.11 $m \cdot s^{-1}$, mean: 1.19 ± 0.11 $m \cdot s^{-1}$). The amputees were effective at increasing their swimming velocity with their unaffected-arm, but not so with their affected-arm.

During the underwater phase of the amputees' unaffected-arm stroke, swimming velocity increased significantly. In contrast, during the affected-arm's underwater stroke, swimming velocity decreased significantly. Interestingly, the amputees' velocity remained above their mean swimming velocity from the end of the unaffected-arm's Push, through the Glide of the affected-arm to the beginning of the affected-arm's Pull (Figure 7.2). This pattern was not repeated on the opposite side of the body. In this case, the amputees' velocity remained below mean swimming velocity from the end of the affected-arm's Glide to the beginning of the unaffected-arm's Push.

Changes in intra-cyclic swimming velocity, during the affected- and unaffected-arm strokes, corresponded to changes in the backward velocity of the arm's most distal point. In the case of the unaffected-arm, the amputees' intra-cyclic swimming velocity increased with an increase in the amputees' backward hand velocity. The highest swimming velocity was reached during the Push phase which coincided with the highest backward hand velocity (Figure 7.3). In able-bodied front crawl, the final Push phase of the underwater stroke is where the highest hand velocities (Payton & Lauder, 1995) and consequently the highest propulsive forces (Maglischo et al., 1988; Schleihauf et al., 1988) are generated. As the highest swimming velocity and highest backward hand velocity occurred during the Push phase, it can be argued that the most propulsive force was also generated in this phase. For unilateral arm amputee front crawl swimmers, the Push phase of the unaffected-arm stroke is critical for the successful generation of propulsion and the forward progression of these swimmers through the water.

A significant decrease in the amputees' intra-cyclic swimming velocity occurred during the underwater stroke of the affected-arm, despite the significant increase in the backward velocity of the stump. At low swimming paces (0.8 - 1.2 $m \cdot s^{-1}$), single-arm amputee front crawl swimmers are able to generate propulsion (Lecrivain et al., 2008; 2010) and increase their intra-cyclic swimming velocity (Payton & Wilcox, 2006) by pulling their affected-arm through the water. In the present study, peak extension velocities of the affected-arm ranged from 6.9 to 11.1 $rad \cdot s^{-1}$ at 400 m pace and 8.1 to 11.7 $rad \cdot s^{-1}$ at 50 m pace. These values were similar to the 7.2 to 10.6 $rad \cdot s^{-1}$ reported by Lecrivain et al. (2010) and the 8.8 to 12.9 $rad \cdot s^{-1}$ by Payton and Wilcox (2006). By pulling the affected-arm through the water with a high angular velocity, single-arm amputees might be attempting to generate propulsion from it. Alternatively, since resistive forces appear to dominate during the pull of the affected-arm, the main role of a fast arm pull might be to shorten the period during which resistive forces dominate.

In the present study, the two fastest swimmers at 50 m pace (1.58 $m \cdot s^{-1}$ and 1.47 $m \cdot s^{-1}$) exhibited the lowest mass centre velocities, expressed relative to the mean swimming velocity, at the end of the Push phase of their affected-arm stroke (88.4% and 89.2%). Conversely, the two slowest swimmers at 50 m pace (1.06 $m \cdot s^{-1}$ and 1.19 $m \cdot s^{-1}$) were able to increase their swimming velocity above mean velocity by the end of the

Push, thus achieving the highest relative mass centre velocities (103.5% and 105.3%). Of these four swimmers, the slowest two exhibited peak arm extension velocities of 11.1 rad·s^{-1} and 10.6 rad·s^{-1}, while the fastest two exhibited peak arm extension velocities of 10.3 rad·s^{-1} and 8.8 rad·s^{-1}. As there exists, for any given swimming pace, a minimum angular velocity at which the affected-arm must be rotated to generate effective propulsion, it seems apparent that the fastest swimmers were not able to achieve this minimum angular velocity. Although propulsion may have been generated, it may not have been enough to offset the resistance experienced by the swimmers, at swimming velocities higher than 1.2 m·s^{-1}. Such experimental findings support those from previous theoretical studies (Lecrivain et al., 2008; 2010).

7.6 Summary and Conclusion

The results from this study show that the amputees' mean intra-cyclic velocity fluctuation (± 15%) did not differ between sprint- and distance-paced swimming. The amputee swimmers attained a higher maximum velocity during their unaffected-arm stroke than they did during their affected-arm stroke. The amputees were effective at increasing their swimming velocity with the unaffected-arm, but not so with their affected-arm. The amputees' intra-cyclic swimming velocity increased significantly during the unaffected-arm's underwater stroke, concomitant with a significant increase in the backward velocity of the hand. In contrast, when pulling their affected-arm through the water, the amputees experienced a significant reduction in their swimming velocity, despite the significant increase in the backward velocity of the stump. These findings imply that unilateral arm amputee front crawl swimmers: (1) need to execute the final backward push of their hand at high velocity to successfully generate propulsion; and (2) may not be able to generate effective propulsion with their affected-arm at swimming velocities above 1.2 m·s^{-1}.

CHAPTER EIGHT

EPILOGUE

(SUMMARY OF FINDINGS, APPLICATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH)

8.1 Epilogue

The general aim of this thesis was to contribute to the body of scientific knowledge regarding the biomechanical characteristics of highly-trained single-arm amputee front crawl swimmers, thus allowing for the application of this knowledge to enhance swimming performance. To achieve this aim, five experimental studies were undertaken, which focused on three main areas: Firstly, how swimmers adjusted their stroke parameters in order to swim faster and which of the swimmers' anthropometric characteristics were related to performance. Secondly, what inter-arm and leg-to-arm coordination patterns were exhibited by these swimmers and how inter-limb coordination was related to the attainment of maximum swimming speed. Thirdly, what arm movements were used by these swimmers during the front crawl stroke cycle and how these movements contributed to propulsion and as a consequence the overall progression of the swimmers through the water.

8.2 Summary of Findings

The aim of Study 1 was to determine the relationships between swimming speed, stroke length and stroke frequency and to assess how these stroke parameters related to selected anthropometric characteristics. Increases in swimming speed above 75% of maximum were achieved by a 5% increase in stroke frequency which coincided with a 2% decrease in stroke length. At sprint pace, stroke frequency was significantly related to swimming speed ($r = .72$; $p < .01$), whereas stroke length was not. Although no correlations existed between stroke length and any anthropometric characteristic, bi-acromial breadth, shoulder girth and upper-arm length all significantly correlated with stroke frequency.

Given the limited information that stroke parameters provide on swimming performance and the fact that the amputees in Study 1 demonstrated a variety of different inter-arm timings, it was decided that an examination of inter-arm coordination was warranted.

The aim of Study 2 was to examine the effect of swimming speed on inter-arm coordination and the inter-relationships between swimming speed, inter-arm coordination and other stroke parameters. Inter-arm coordination of the amputee swimmers did not change as swimming speed was increased up to maximum. Swimmers showed significantly more ($p < .01$) catch-up coordination of their affected-arm compared to their unaffected-arm. When sprinting, the fastest swimmers, who had the highest stroke frequencies, exhibited the least amount of catch-up of their affected-arm.

In Study 2 an examination of the amputees' leg kick in relation to the arm stroke was not undertaken. Given that the asymmetrical nature of the amputees' inter-arm coordination may have influenced their leg kick action, it was decided to investigate the leg-to-arm coordination patterns of these swimmers.

The aim of Study 3 was to examine the effect of swimming speed on leg kick and arm stroke coordination. With increasing speed, swimmers did not change the number of kicks they performed per arm stroke cycle. When sprinting, swimmers predominantly used a six-beat leg kick ($n = 10$), although four-beat ($n = 2$) and eight-beat leg kicks ($n = 1$) were also used. There was significant temporal asymmetry ($p < .01$) between the swimmers' affected- and unaffected-arm stroke phases. In contrast, the kicking phases between legs were symmetrical. Asymmetrical leg-to-arm coordination existed as a consequence of asymmetrical inter-arm coordination and symmetrical inter-leg coordination.

In Studies 1, 2 and 3, the motion of the swimmers' front crawl stroke was examined using a two dimensional analysis approach. Given that swimming is a three-dimensional movement, three-dimensional analysis techniques must be used to fully and accurately determine the exact motion of a swimmer's limbs and a swimmer's centre of mass. Studies 4 and 5 are novel, in that they used whole body, three dimensional analysis techniques to examine the upper extremity kinematics and intra-cyclic velocity fluctuations of ten highly-trained unilateral arm amputee front crawl swimmers, at two different swimming paces.

The aim of Study 4 was to determine whether upper extremity kinematics differed between sprint- and distance-paced swimming and to examine the inter-relationships between selected upper extremity kinematics and swimming performance. Upper extremity kinematics were not generally different between swimming paces. The amputees pulled their affected-arm through the water differently to their unaffected arm. In comparison to able-bodied swimmers, the amputees' used a more linear hand path trajectory. During the unaffected-arm Insweep, the amputees flexed their elbow less, and exhibited less horizontal shoulder flexion, shoulder roll and inward hand velocity compared to able-bodied swimmers. The amputees conformed to one of three distinct movement patterns when pulling their affected-arm through the water. When viewed from the front, swimmers pulled their affected-arm through the water: (1) in a wide arc outside the shoulder-line ($n = 4$); (2) underneath and in-line with the shoulder ($n = 4$); or (3) in a narrow arc inside the shoulder-line ($n = 2$). The amputees used significantly more ($p < .05$) shoulder roll during the recovery of their unaffected-arm than during the affected-arm recovery. Although there was a moderate negative correlation between swimming speed and stroke length (at 50 m pace $r = -.33$; at 400 m pace $r = -.56$), swimmers who had the longest strokes had the least amount of arm slippage and exhibited the lowest backward arm velocities, relative to the water, during the middle part of the underwater stroke.

In Study 4, the effectiveness of the amputees' affected- and unaffected-arm pull was not assessed. Given that the velocity of the arm, relative to the water is important for generating propulsion and the horizontal velocity fluctuation of a swimmer's mass centre provides an indirect measure of the propulsive and resistive forces acting on a swimmer, it was decided to investigate the intra-cyclic nature of the amputees' front crawl stroke.

The aim of Study 5 was to establish whether intra-cyclic velocity fluctuations differed between sprint- and distance-paced swimming and to determine the influence of the backward velocity of the arms' most distal point on intra-cyclic swimming velocity. The amputees' mean intra-cyclic velocity fluctuation (± 15%) did not differ between sprint- and distance-paced swimming. The amputees' intra-cyclic swimming velocity increased significantly ($p < .01$) during the unaffected-arm's underwater stroke, concomitant with a significant increase ($p < .01$) in the backward velocity of the hand. In contrast, when pulling their affected-arm through the water, the amputees experienced a significant reduction ($p < .01$) in their swimming velocity, despite the significant increase ($p < .01$) in the backward velocity of the stump.

8.3 Applications and Recommendations

The findings of this thesis are of practical benefit to unilateral arm-amputee front crawl swimmers and to those who coach and teach them. The main findings of this thesis have allowed criteria to be established for correct front crawl swimming by single-arm amputees. The criteria form part of an empirical evidence-base, upon which coaches can plan practices for their swimmers to improve the effectiveness of the swimmers' stroke. These criteria could be used by swimming teachers to ensure that swimmers who are learning to swim are taught the correct basic stroke technique. The criteria could also be used as a comparative benchmark, against which technical changes brought about by adaptations to training could be assessed. This would be of use when monitoring technical performances during the course of a training season. The following are evidence-based criteria for single-arm amputee front crawl swimmers:

1. Swimmers with a single-arm amputation increase their swimming speed, over a range of speeds, by increasing their stroke frequency which coincides with a decrease in stroke length. This is similar to able-bodied front crawl swimmers (Craig & Pendergast, 1979; Hay, 2002).
2. When sprinting, faster single-arm amputee swimmers, who have broader shoulders and longer arms, do not use longer strokes; rather they use higher stroke frequencies than their slower, more slender counterparts. This is in contrast to able-bodied front crawl swimmers (Arellano et al., 1994; Craig & Pendergast, 1979; Grimston & Hay, 1986; Pelayo et al., 1996).
3. Stroke length should not be completely ignored however, as technical improvements in a swimmer's performance over a long term should be reflected in their ability to swim at a given speed with a longer stroke. Swimmers with a single-arm amputation, who use the longest strokes, have the least amount of arm slippage and exhibit the lowest backward arm velocities, relative to the water, during the middle part of their underwater arm stroke.
4. As swimmers with a single-arm amputation increase their swimming speed, over a range of speeds, their asymmetrical inter-arm coordination does not change. This is in contrast to able-bodied front crawl swimmers (Chollet et al., 2000; Seifert et al., 2004).
5. When sprinting, the ability of a single-arm amputee swimmer to attain a high stroke frequency is influenced mainly by the amount of catch-up of their affected-arm. This is similar to able-bodied front crawl swimmers (Chollet et al., 2000; Seifert et al., 2004). Reducing the time delay before initiating the affected-

arm pull appears to be a beneficial strategy which allows for attainment of the highest stroke frequencies and swimming speeds.

6. Swimmers with a single-arm amputation predominantly use a six-beat leg kick to swim over a range of speeds. However, unlike able-bodied front crawl swimmers (Hue et al., 2003; Millet et al., 2002), single-arm amputees do not change the number of leg kicks they execute per arm stroke cycle as they swim faster.

7. Swimmers with a single-arm amputation coordinate their leg kick with their arm stroke, rather than kicking their legs independently of moving their arms. They align their leg kick with their unaffected-arm as able-bodied front crawl swimmers do for both arms (Maglischo, 2003; Yanai, 2003). Rhythmically aligning the leg kicks with particular arm stroke phases might enhance performance and may maintain the stable repetition of the overall arm stroke cycle.

8. Swimmers with a single-arm amputation do not generally change their upper extremity limb movements between sprint- and distance-paced swimming. This is similar to able-bodied front crawl swimmers (McCabe et al., 2011).

9. Unlike able-bodied front crawl swimmers (Payton & Lauder, 1995; Scheihauf et al., 1988), swimmers with a single-arm amputation do not use pronounced medial hand movements during their Insweep. This may be due to single-arm amputee swimmers needing less medially directed hydrodynamic force to control body roll or them relying more on a backward hand movement to generate propulsion.

10. Swimmers with a single-arm amputation attain their highest swimming velocity and highest backward hand velocity during the final push phase of the underwater arm stroke. This is similar to able-bodied front crawl swimmers

(Maglischo et al., 1988; Schleihauf et al., 1988). As it is likely that the highest propulsive forces are also generated during the Push phase, single-arm amputee swimmers should execute the final backward push of their hand at high velocity to successfully generate propulsion.

11. When swimming slowly (below 1.2 $m \cdot s^{-1}$), a few single-arm amputee swimmers are able to increase their swimming velocity during the pull of their affected-arm. This is in agreement with previous studies (Lecrivain et al., 2010; Payton & Wilcox, 2006). Most single-arm amputee swimmers however, are not able to increase their swimming velocity with their affected-arm when swimming faster than 1.2 $m \cdot s^{-1}$, suggesting that they are unable to generate effective propulsion with their affected-arm.

8.4 Future Research

This thesis has gone some way in addressing the gap within the impairment specific swimming literature, by examining the biomechanical characteristics of highly-trained single-arm amputee front crawl swimmers. However, there still remain areas for future research.

Throughout the thesis it was evident that within the group of unilateral arm amputee front crawl swimmers a variety of inter-individual differences existed. For example in Study 1, Chapter 3, some swimmers did not conform well to the group mean swimming speed versus stroke frequency curve; in Study 2, Chapter 4, large standard deviations indicated large inter-arm coordination variability within the group; in Study 3, Chapter 5, different kick beat patterns were evident ranging from a four-beat kick to an eight-beat kick; in Study 4, Chapter 6, swimmers pull their affect-arm through the water using one of three observed movement patterns. Further examination of the individual swimmer profiles might yield further, useful insights into how highly-trained single-arm amputee swimmers functionally adapt their motor organisation to swim front crawl.

In Study 4, Chapter 6, the single-arm amputee swimmers used less elbow flexion and a smaller medial hand insweep, when compared to able-bodied swimmers. It was speculated that this might have been related to the amputees needing less torque about their long axis to roll their body back towards the neutral position, compared to their able-bodied counterparts. Furthermore, given that the dominant mechanism for generating body roll in able-bodied front crawl could not explain the greater shoulder roll that occurred when the amputees' unaffected-arm was recovered over the water, an examination into the medio-lateral arm movements and their link to body roll and the torque acting about the swimmers' long axis is warranted.

In Study 4, Chapter 6, the single-arm amputee swimmers used significantly more shoulder roll during the recovery of their unaffected-arm than during the affected-arm recovery. This has important implications for which side these swimmers should breathe. Without sufficient body roll, the act of breathing becomes difficult to execute without it interfering with a swimmer's ability to produce propulsion, or with it increasing the amount of resistance experienced by their body. Examining the effect of the breathing action, to the affected- and unaffected-side, on upper extremity kinematics of unilateral arm amputee front crawl swimmers would be of great practical value.

In Study 5, Chapter 7, when examining each swimmer's intra-cyclic velocity-time curve, a clear number of maxima were evident which coincided with the execution of the swimmer's leg kicks. This kicking action would have contributed to overall propulsion. However, the relative contribution of the leg kick to swimming performance is unknown for unilateral arm amputee front crawl swimmers and warrants further study.

In Study 5, Chapter 7, the single-arm amputee swimmers were unable to increase their swimming velocity using their affected-arm, suggesting that they were not able to generate effective propulsion with it. This brings into question the use of the affected-arm during the front crawl stroke. It may be the case that for unilateral arm amputee front crawl swimmers, swimming single-arm front crawl or indeed single-arm butterfly, where the affected-arm is held stationary in front of the body, may be a more successful swimming technique than swimming front crawl with both arms. Research is needed to examine the effect of single-arm swimming on intra-cyclic velocity fluctuations of unilateral arm amputee front crawl swimmers.

8.5 Conclusion

This thesis has contributed to the body of scientific knowledge regarding the biomechanical characteristics of highly-trained single-arm amputee front crawl swimmers. The findings of this thesis suggest that when single-arm front crawl swimmers are sprinting: (a) the attainment of a high stroke frequency is more important than swimming with the longest possible stroke; (b) reducing the length of time the affected-arm is held stationary in front of the body will help attain a high stroke frequency; (c) the rhythmical alignment of leg kicks to arm strokes may enhance performance and contribute to the stability of inter-arm coordination; (d) amputees use a more linear underwater hand movement, than able-bodied swimmers and use one of three distinct movement patterns to pull their affected-arm through the water; (e) increases in intra-cyclic swimming velocity can be achieved with the unaffected-arm, but not so with the affected-arm. The findings of this thesis will be of interest to scientists working in the area of swimming biomechanics. They should also be of some practical benefit to unilateral arm-amputee front crawl swimmers and to those who coach and teach them.

CHAPTER NINE

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APPENDIX I

PARTICIPANT DETAILS

Table I. Details of swimmers who consented to participant in this programme of research.

Participant	Gender	Age (years)	Height (metres)	Mass (kilograms)	50 m PB (seconds)	World Ranking	IPC Class	Swim Training (metres/week)	Amputation Type	Affected Side
1	Female	19.7	1.67	57.7	34.74	-	S9	10000	Congenital	Left
2	Female	19.6	1.66	67.4	33.73	41	S9	34000	Congenital	Left
3	Female	19.1	1.60	61.7	39.60	-	S9	35000	Congenital	Right
4	Female	19.1	1.67	56.9	30.76	7	S9	40000	Congenital	Left
5	Female	14.5	1.67	57.5	30.66	5	S9	17000	Congenital	Right
6	Female	14.1	1.66	61.5	33.96	44	S9	23000	Congenital	Left
7 [a]	Female	13.8	1.67	51.3	35.21	-	S9	21000	Congenital	Left
8	Female	12.8	1.64	60.3	33.99	45	S9	27000	Congenital	Left
9	Female	12.2	1.57	44.8	33.61	38	S9	20000	Congenital	Left
10 [a]	Female	18.9	1.69	69.1	31.57	12	S9	41000	Accident	Left
11	Male	21.3	1.84	99.1	28.63	30	S9	15000	Congenital	Right
12	Male	16.1	1.86	71.6	30.77	24	S8	20000	Congenital	Right
13 [a]	Male	18.7	1.79	67.5	27.92	24	S9	30000	Congenital	Left

[a] These participants only took part in the studies described in Chapters 3, 4 and 5.

APPENDIX II

INFORMED CONSENT FORMS

Informed Consent Form (to be retained by the investigator)

Participant:

Name: **Sex**: Male / Female

Date of Birth:

Supervisor/Principal Investigator: Mr Conor Osborough.

Investigator/Collaborators: Dr Carl Payton.

Ethics Committee Approval Number: **2006.07.04a**

Project Title: The spatial, temporal and co-ordination characteristics of highly trained, uni-lateral, arm amputee, front crawl swimmers.

Purpose of study and brief description of procedures:

The study that you have been invited to take part in will look at how the co-ordination between your left and right arm changes at different swimming speeds. The information collected will be used to establish possible training adaptations and race strategies
After a 600m warm up you will be asked to swim five 50metre front crawl swims at different swimming speeds. 10 minutes recovery will be allowed between each swim. After this you will be asked to swim a single, maximal, non-paced 100metre front crawl swim. Each swimming performance will be videotaped from both sides of the pool. Before, during and after the swimming trials, blood lactate concentrations will be recorded via the earlobe. After the test you will be asked to swim a 600m cool-down.
The risk of injury when you swim will be small, since we will only ask you to swim at exercise intensities that are the same as those practiced during normal training, which you will be familiar and comfortable with. An opportunity to ask any questions on any aspect of the study will be provided. All questions will be answered. If you agree to take part in this study, you are free to withdraw at any time without having to give any reasons. At no point will you be disadvantaged if you decide to participate or not.
In any training-history questionnaire you are free to refuse answers to any specific questions or items. The information obtained from the study will remain confidential and stored by the investigators in adherence with the Data Protection Act.

Participant Statement

I fully understand what is involved in taking part in this study. Any questions I have about the study, or my participation in it, have been answered to my satisfaction. I understand that I do not have to take part and that I may decide to withdraw from the study at any point without prejudice. I have had my attention drawn to the document 'Ethical Regulations for the Use of Humans in Research'. My concerns regarding this study have been answered and such further concerns as I have during the time of the study will be responded to. It has been made clear to me that, should I feel that these Regulations are being infringed or that my interests are otherwise being ignored, neglected or denied, I should inform the Chair of the Ethics Committee of the Department of Exercise and Sport Science, Manchester Metropolitan University, Hassall Road, Alsager, Cheshire, ST7 2HL who will undertake to investigate my complaint.

Signed .... Date ....

I certify that the details of this study have been fully explained and
described in writing to .... and have been
understood by him/her and that I consent to his/her participation in this study.

Signed .... Date ....
(parental consent for minors only)

Informed Consent Form (to be retained by the investigator)

Participant:

Name: **Sex**: Male / Female

Date of Birth:

Supervisor/Principal Investigator: Mr Conor Osborough.

Investigator/Collaborators: Dr Carl Payton.

Ethics Committee Approval Number: **2006.07.04b**

Project Title: Whole body spatial, temporal and kinematic parameters of highly trained uni-lateral, arm amputee, front crawl swimmers.

Purpose of study and brief description of procedures:

The study that you have been invited to take part in will look at how you perform your swimming movement patterns. The information collected will be used to increase our understanding of the mechanics of arm amputee front crawl swimming.
After a 600m warm up you will be asked to swim four 25metre swims at your 100m race distance pace. 2 minutes recovery will be allowed between each swim. Each swimming performance will be videotaped from both sides of the pool. Before the swimming trials it will be necessary to mark eighteen joint centre locations on you using marker pen, so that the length of your arm, trunk and leg segments can be determined from the video images. You will be shown what is going to be done in advance. After the test you will be asked to swim a 600m cool-down.
The risk of injury when you swim will be small, since we will only ask you to swim at an exercise intensity that is the same as that practiced during normal training, which you will be familiar and comfortable with. An opportunity to ask any questions on any aspect of the study will be provided. All questions will be answered. If you agree to take part in this study, you are free to withdraw at any time without having to give any reasons. At no point will you be disadvantaged if you decide to participate or not.
In any training-history questionnaire you are free to refuse answers to any specific questions or items. The information obtained from the study will remain confidential and stored by the investigators in adherence with the Data Protection Act.

Participant Statement

I fully understand what is involved in taking part in this study. Any questions I have about the study, or my participation in it, have been answered to my satisfaction. I understand that I do not have to take part and that I may decide to withdraw from the study at any point without prejudice. I have had my attention drawn to the document 'Ethical Regulations for the Use of Humans in Research'. My concerns regarding this study have been answered and such further concerns as I have during the time of the study will be responded to. It has been made clear to me that, should I feel that these Regulations are being infringed or that my interests are otherwise being ignored, neglected or denied, I should inform the Chair of the Ethics Committee of the Department of Exercise and Sport Science, Manchester Metropolitan University, Hassall Road, Alsager, Cheshire, ST7 2HL who will undertake to investigate my complaint.

Signed .... Date ....

I certify that the details of this study have been fully explained and
described in writing to .... and have been
understood by him/her and that I consent to his/her participation in this study.

Signed .... Date ....
(parental consent for minors only)

APPENDIX III

INDIVIDUAL SWIMMER'S PLOTS FOR CHANGES IN STROKE LENGTH AND STROKE FREQUENCY WITH AN INCREASE IN SWIMMING SPEED

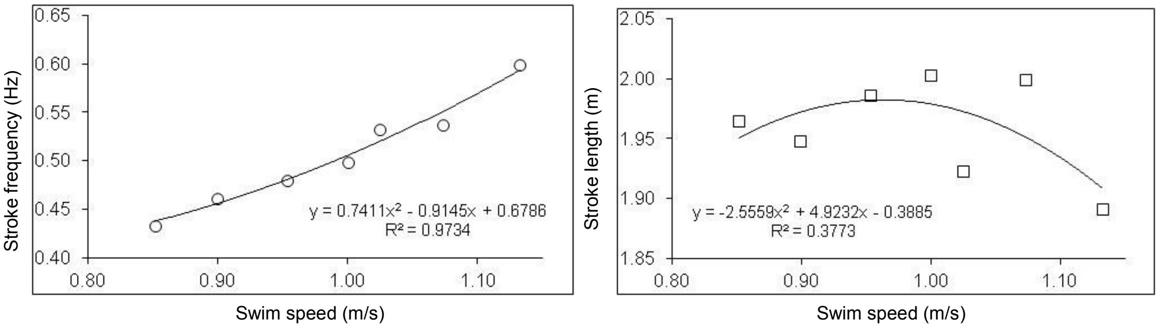

Figure IV. 1 Participant 1 (♂): SF versus SS (left) and SL versus SS (right).

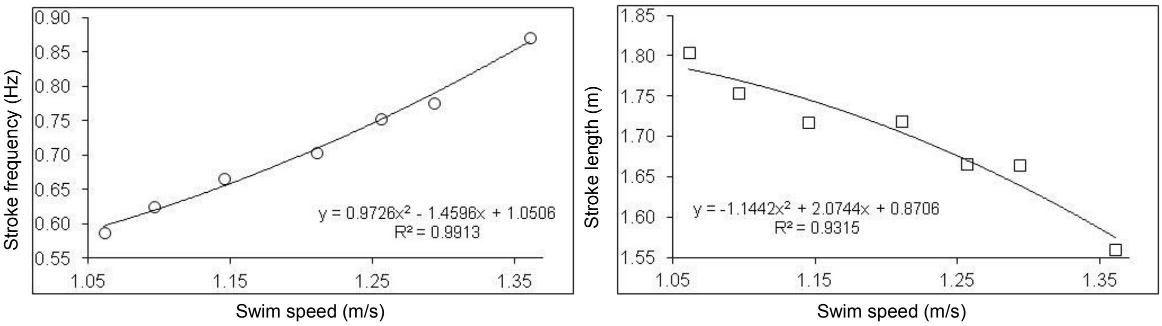

Figure IV. 2 Participant 2 (♂): SF versus SS (left) and SL versus SS (right).

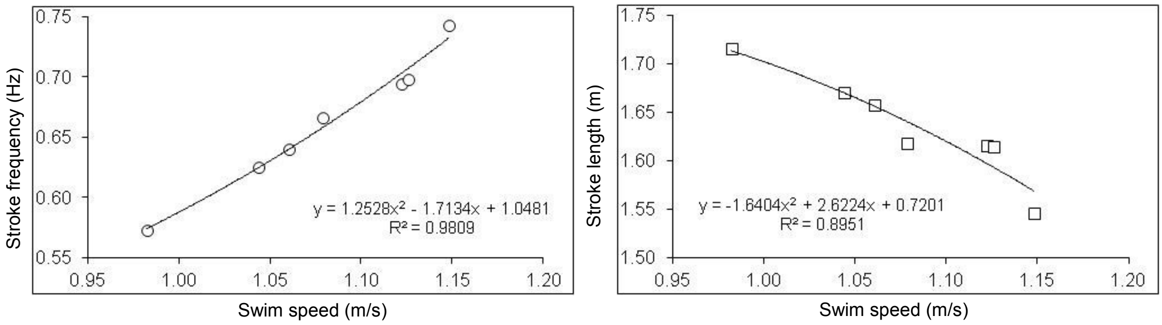

Figure IV. 3 Participant 3 (♂): SF versus SS (left) and SL versus SS (right).

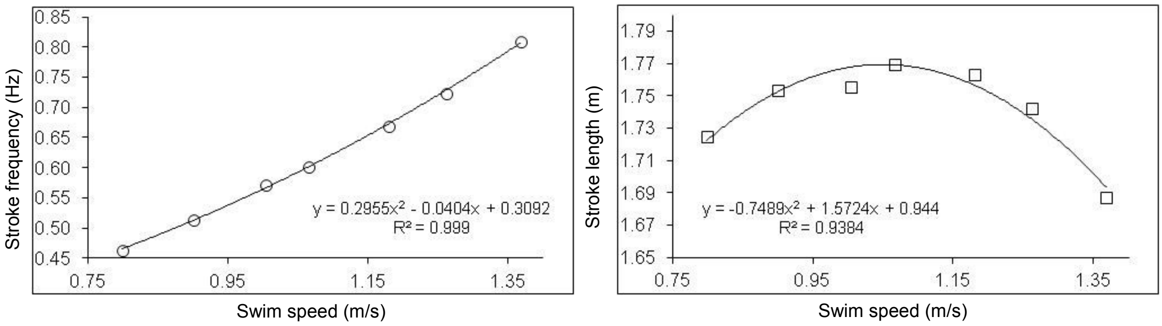

Figure IV. 4 Participant 4 (♂): SF versus SS (left) and SL versus SS (right).

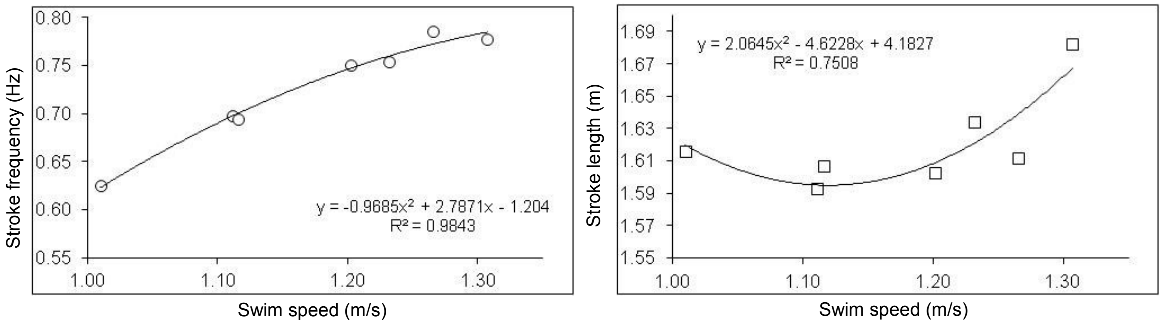

Figure IV. 5 Participant 5 (♂): SF versus SS (left) and SL versus SS (right).

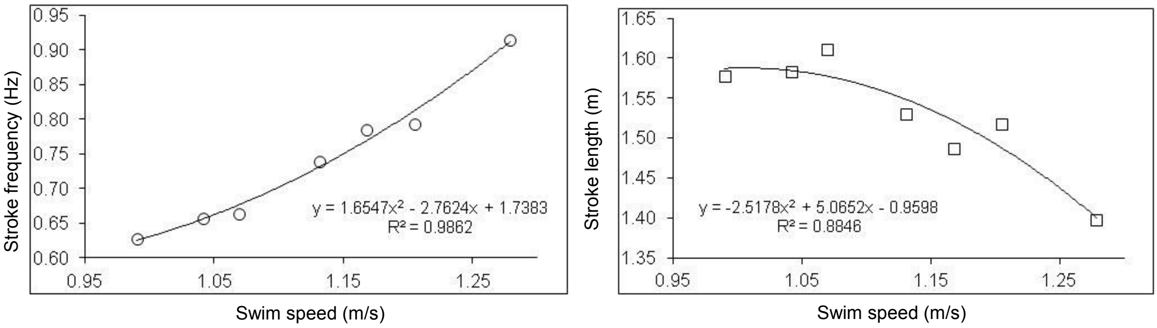

Figure IV. 6 Participant 6 (♂): SF versus SS (left) and SL versus SS (right).

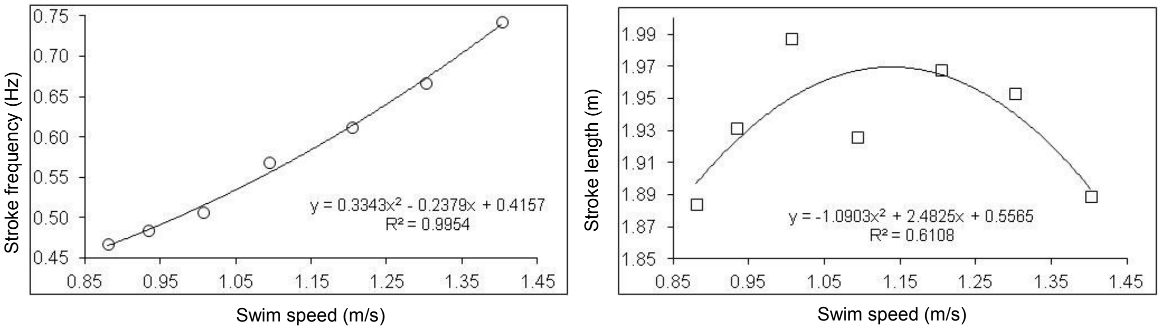

Figure IV. 7 Participant 7 (♂): SF versus SS (left) and SL versus SS (right).

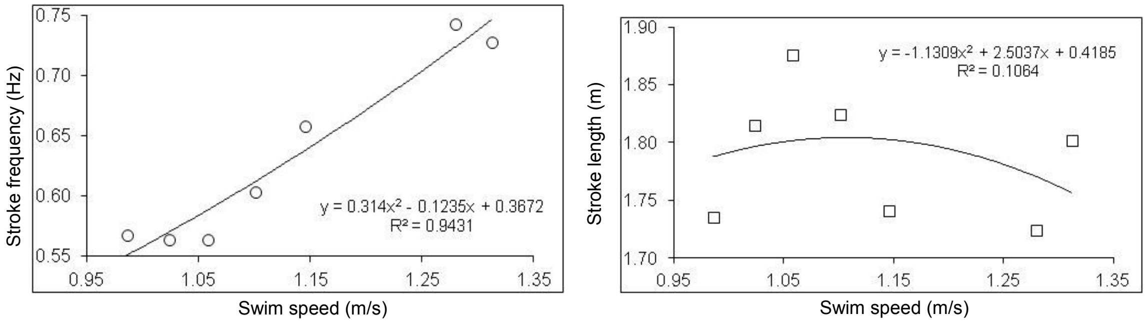

Figure IV. 8 Participant 8 (♂): SF versus SS (left) and SL versus SS (right).

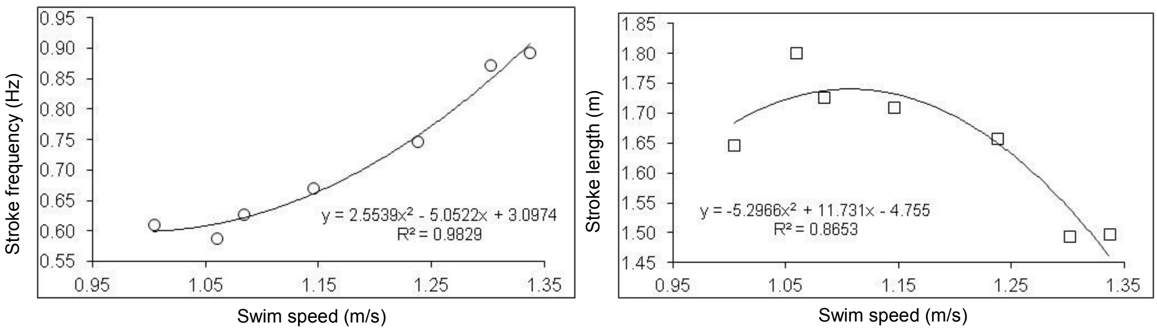

Figure IV. 9 Participant 9 (♂): SF versus SS (left) and SL versus SS (right).

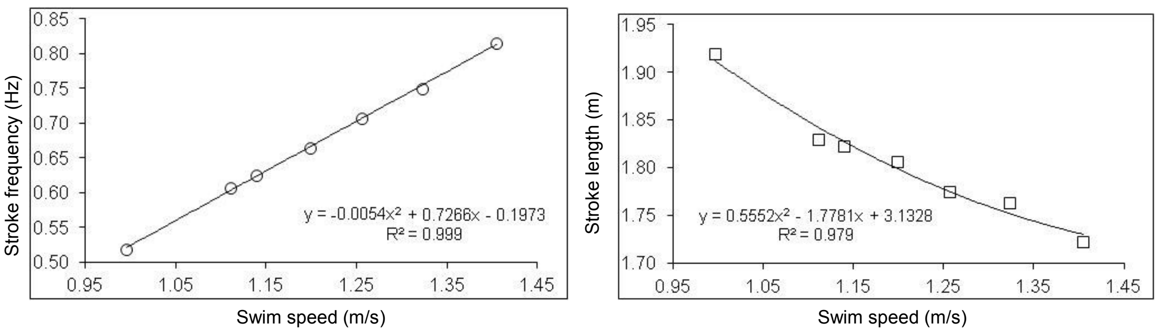

Figure IV. 10 Participant 10 (♂): SF versus SS (left) and SL versus SS (right).

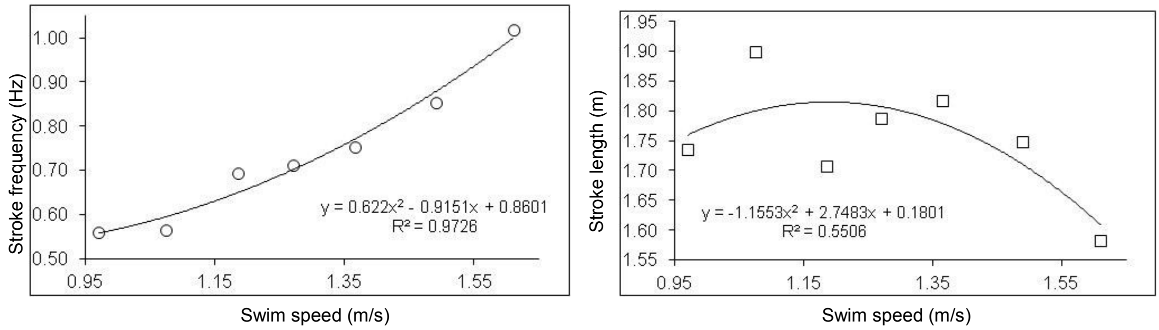

Figure IV. 11 Participant 11 (♀): SF versus SS (left) and SL versus SS (right).

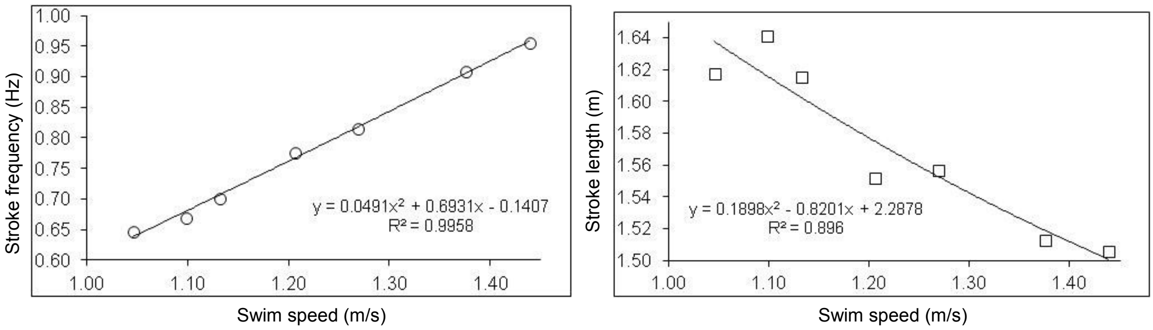

Figure IV. 12 Participant 12 (♀): SF versus SS (left) and SL versus SS (right).

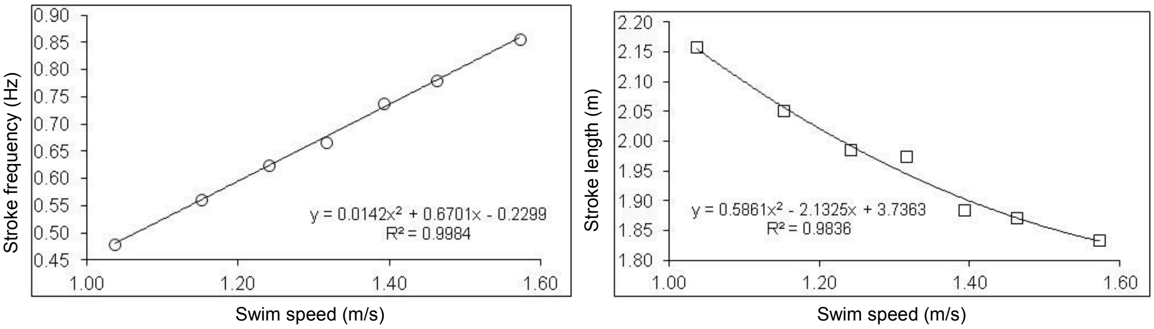

Figure IV. 13 Participant 13 (♀): SF versus SS (left) and SL versus SS (right).

APPENDIX IV

INDIVIDUAL SWIMMER'S PLOTS FOR CHANGES IN INTER-ARM COORDINATION WITH AN INCREASE IN SWIMMING SPEED

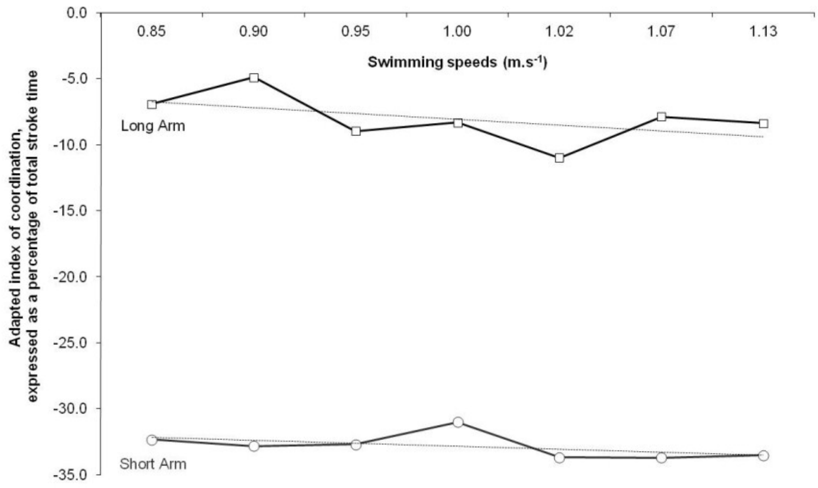

Figure V. 1 Participant 1 (♂): IdC_{af} and IdC_{un} with an increase in SS.

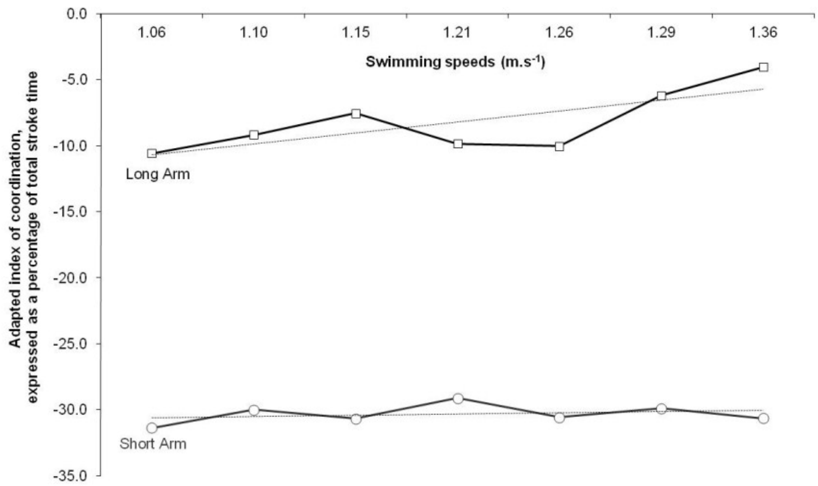

Figure V. 2 Participant 2 (♂):IdC_{af} and IdC_{un} with an increase in SS.

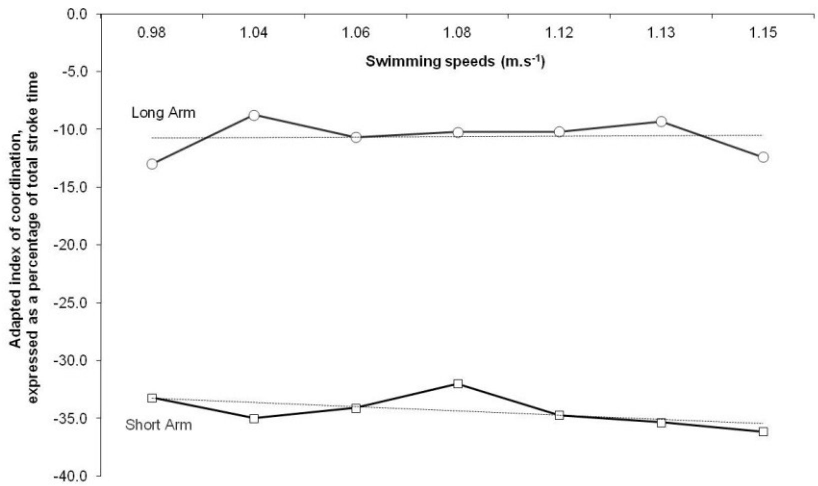

Figure V. 3 Participant 3 (♂):IdC_{af} and IdC_{un} with an increase in SS.

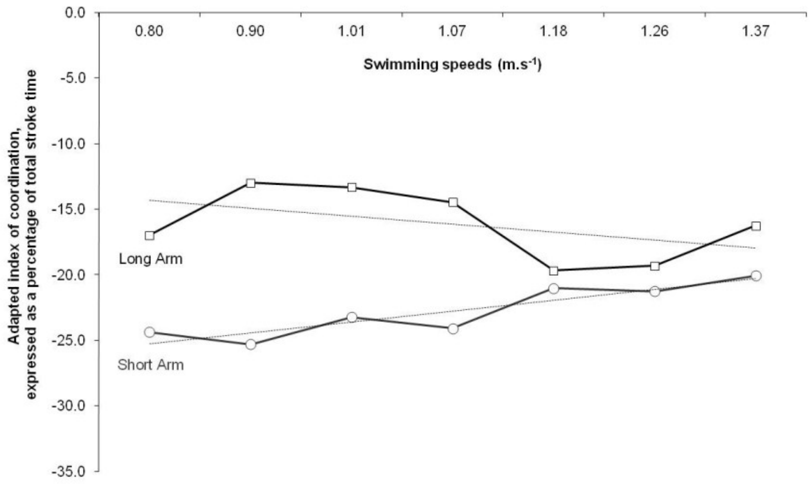

Figure V. 4 Participant 4 (♂):IdC_{af} and IdC_{un} with an increase in SS.

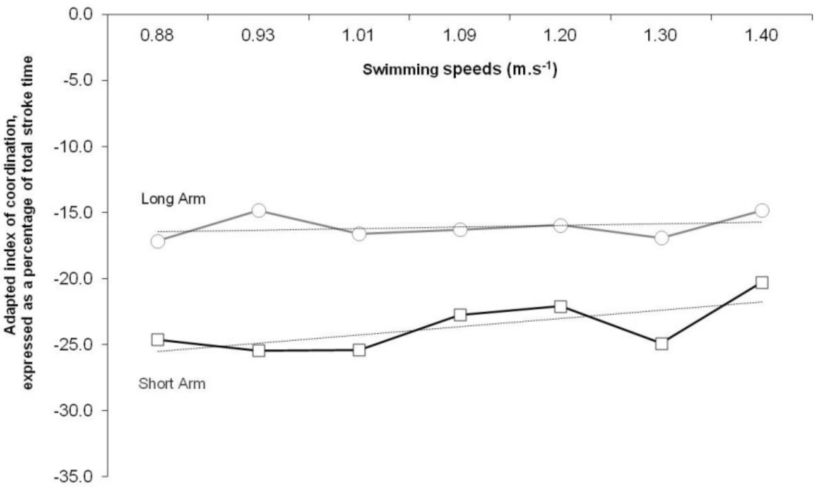

Figure V. 5 Participant 5 (♂):IdC_{af} and IdC_{un} with an increase in SS.

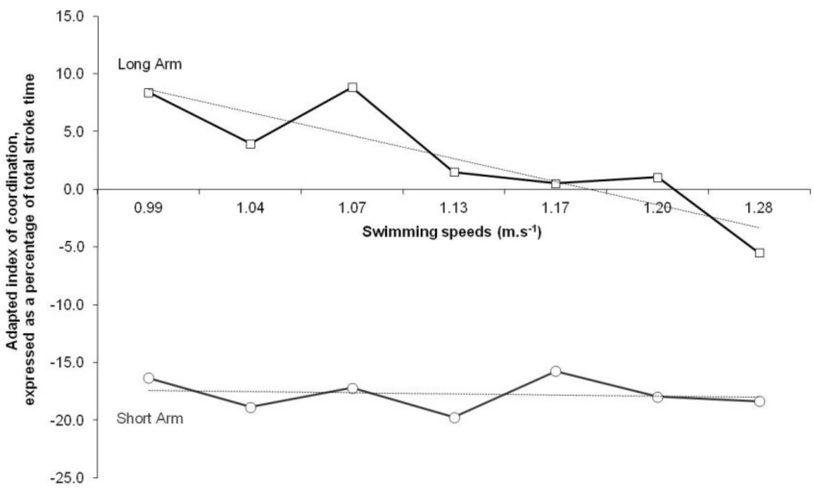

Figure V. 6 Participant 6 (♂):IdC_{af} and IdC_{un} with an increase in SS.

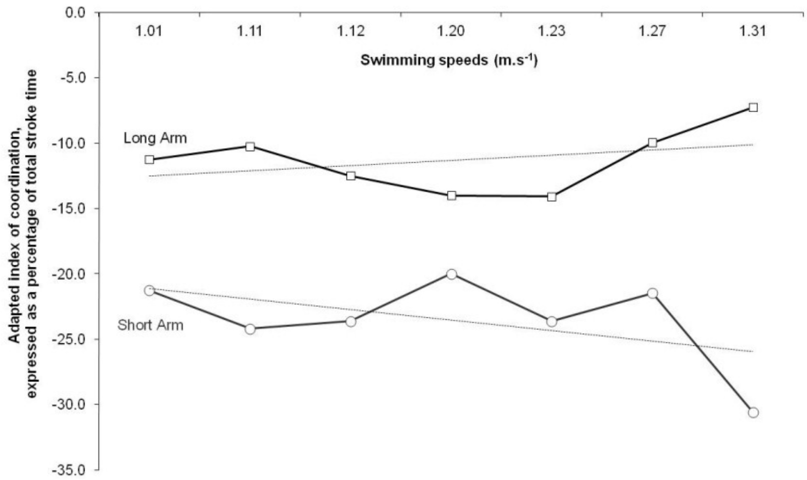

Figure V. 7 Participant 7 (♂):IdC$_{af}$ and IdC$_{un}$ with an increase in SS.

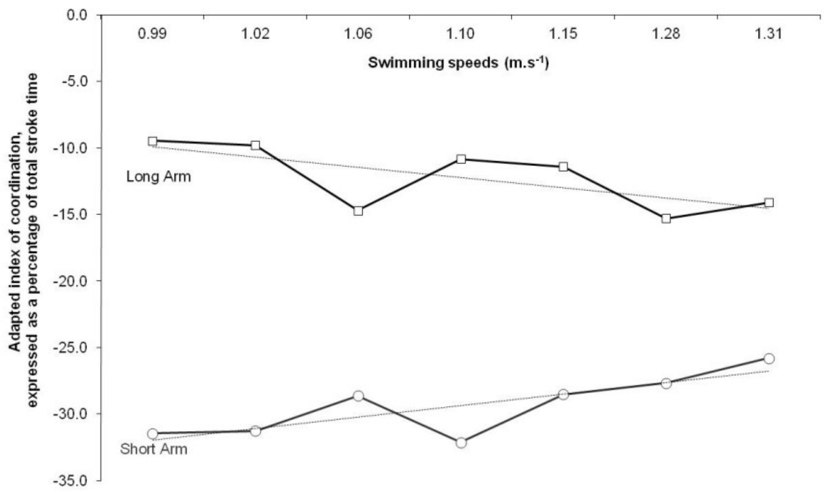

Figure V. 8 Participant 8 (♂):IdC$_{af}$ and IdC$_{un}$ with an increase in SS.

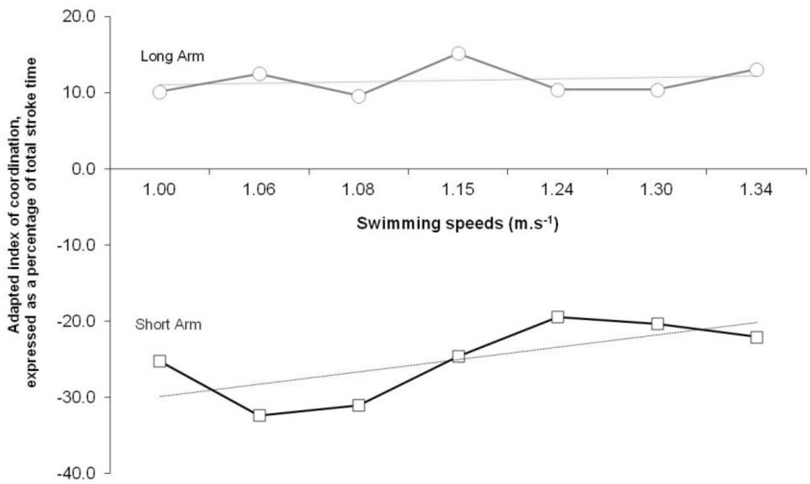

Figure V. 9 Participant 9 (♂):IdC$_{af}$ and IdC$_{un}$ with an increase in SS.

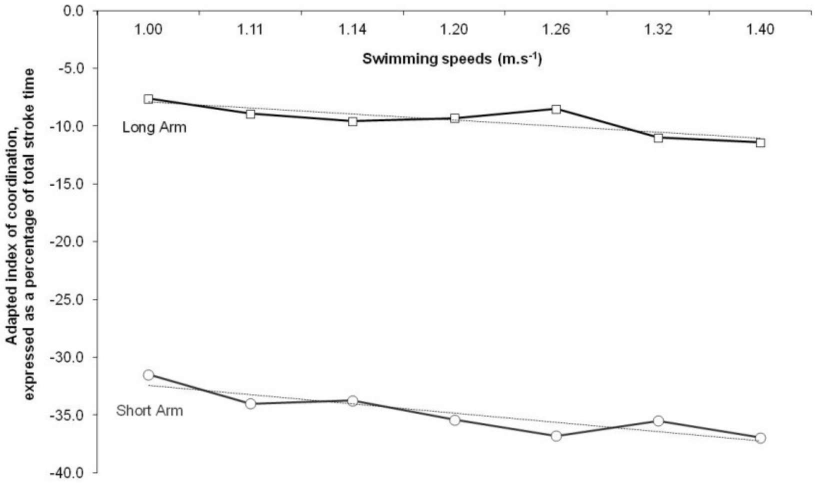

Figure V. 10 Participant 10 (♂):IdC_{af} and IdC_{un} with an increase in SS.

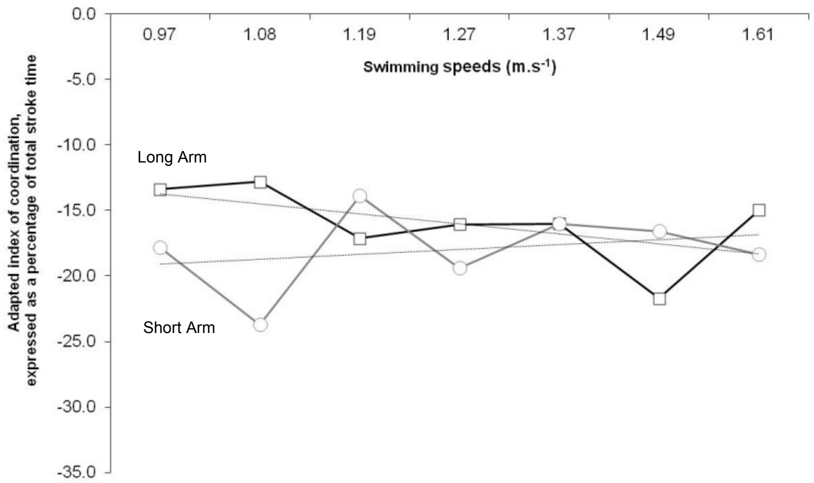

Figure V. 11 Participant 11 (♀):IdC_{af} and IdC_{un} with an increase in SS.

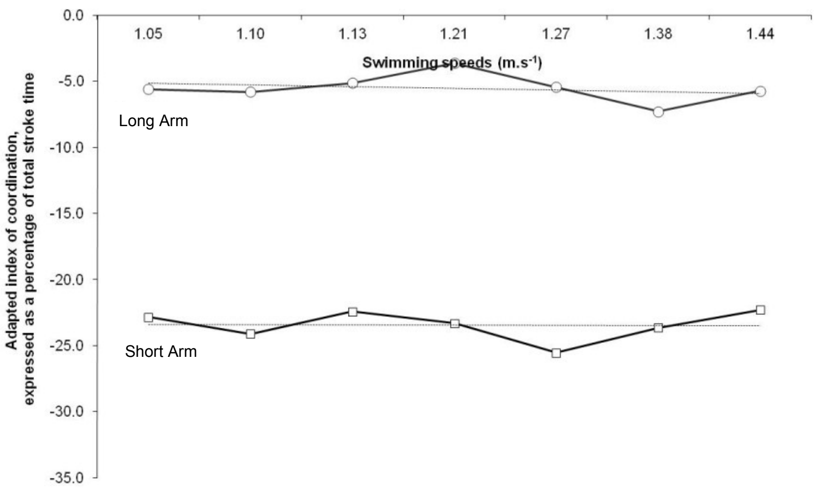

Figure V. 12 Participant 12 (♀):IdC_{af} and IdC_{un} with an increase in SS.

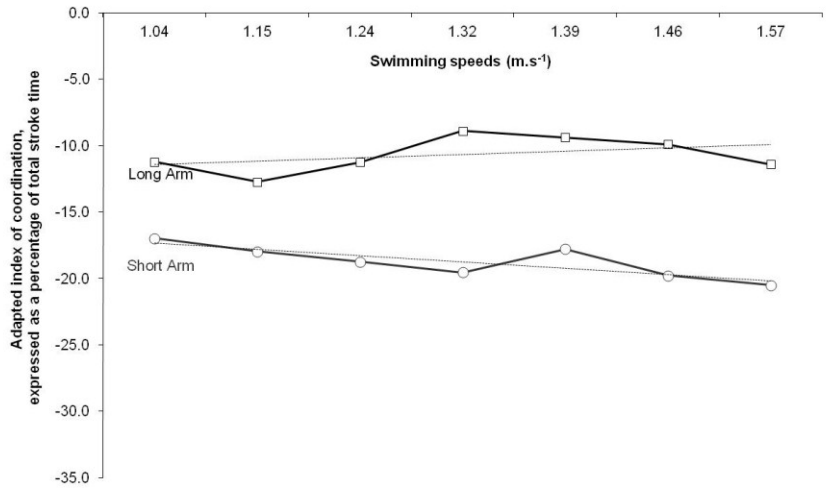

Figure V. 13 Participant 13 (♀):IdC_{af} and IdC_{un} with an increase in SS.

APPENDIX V

INDIVIDUAL SWIMMER'S PLOTS FOR UPPER-LIMB TRAJECTORIES DURING SPRINT- AND DISTANCE-PACED SWIMMING

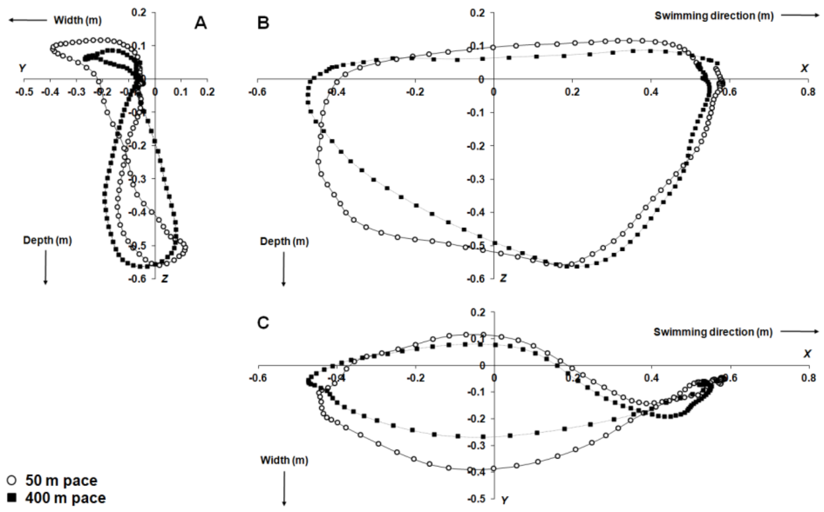

Figure VI. 1 Participant 1 (♂): Right hand trajectory, front (A), side (B), above (C) views.

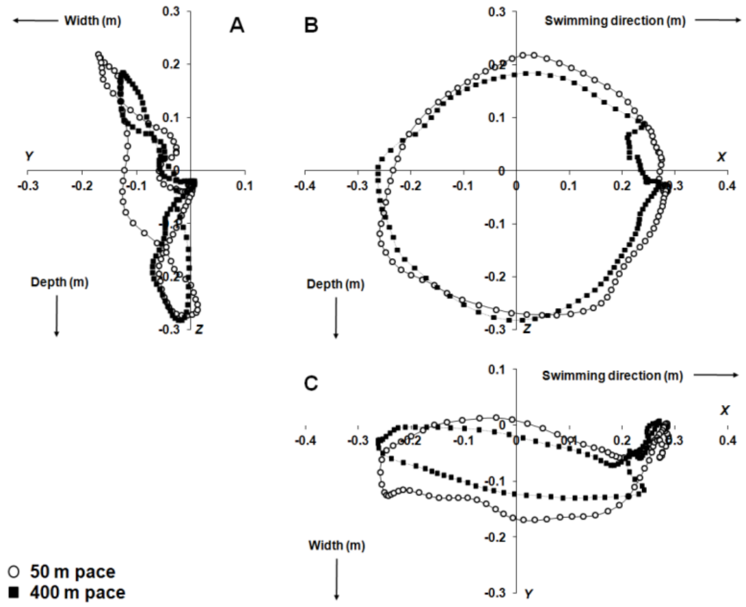

Figure VI. 2 Participant 1 (♂): Unaffected-elbow trajectory, front (A), side (B), above (C) views.

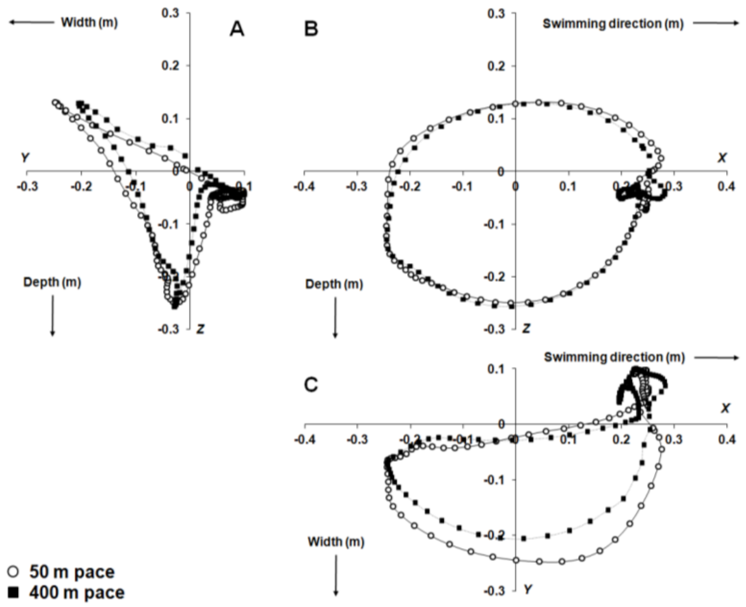

Figure VI. 3 Participant 1 (♂): Affected-elbow trajectory, front (A), side (B), above (C) views.

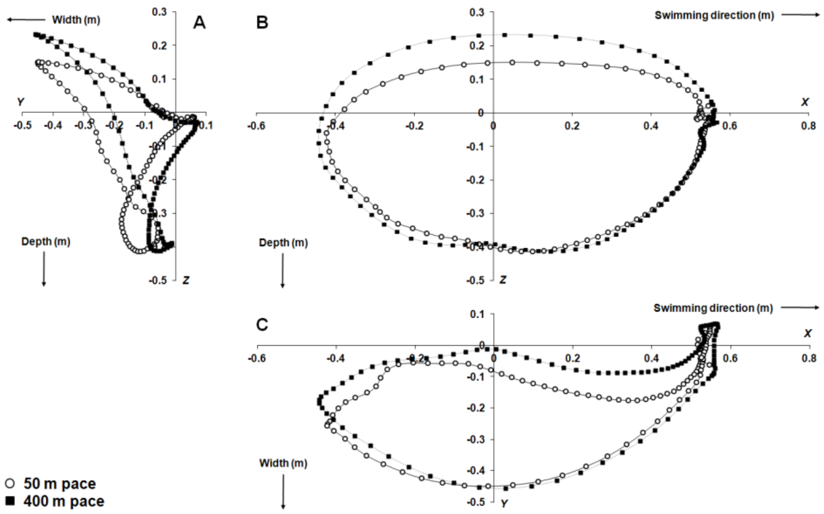

Figure VI. 4 Participant 2 (♂): Right hand trajectory, front (A), side (B), above (C) views.

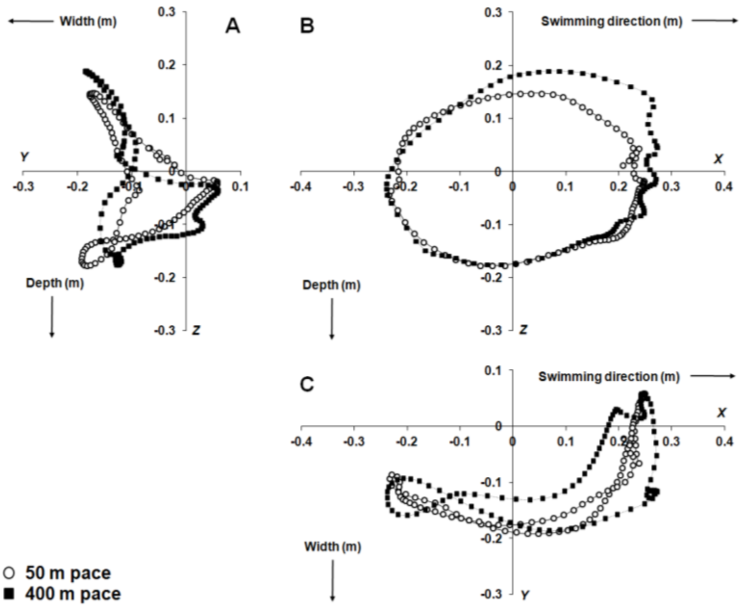

Figure VI. 5 Participant 2 (♂): Unaffected-elbow trajectory, front (A), side (B), above (C) views.

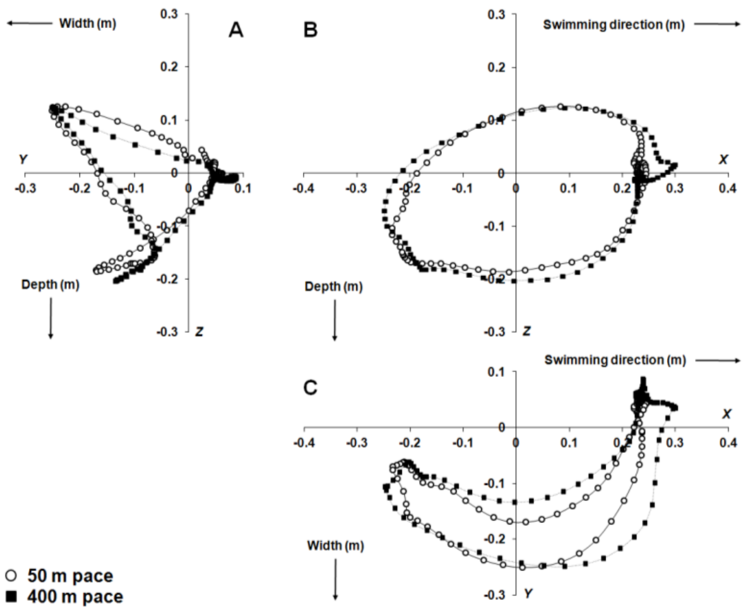

Figure VI. 6 Participant 2 (♂): Affected-elbow trajectory, front (A), side (B), above (C) views.

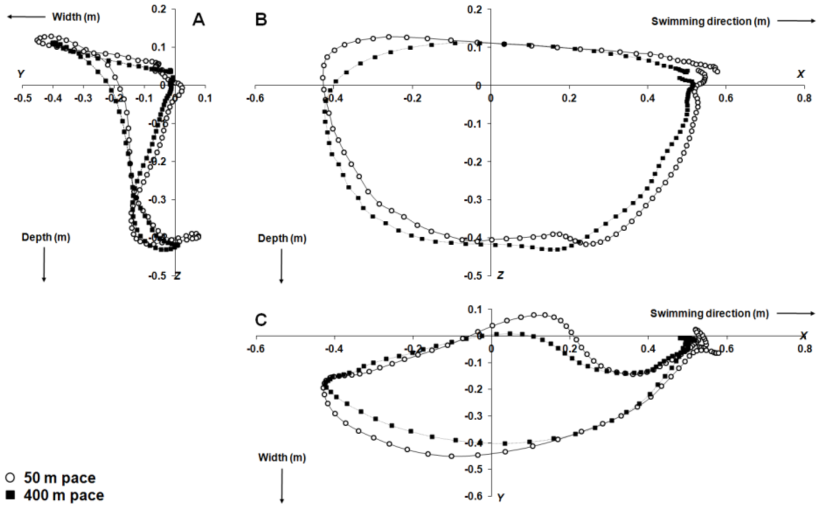

Figure VI. 7 Participant 3 (♂): Right hand trajectory, front (A), side (B), above (C) views.

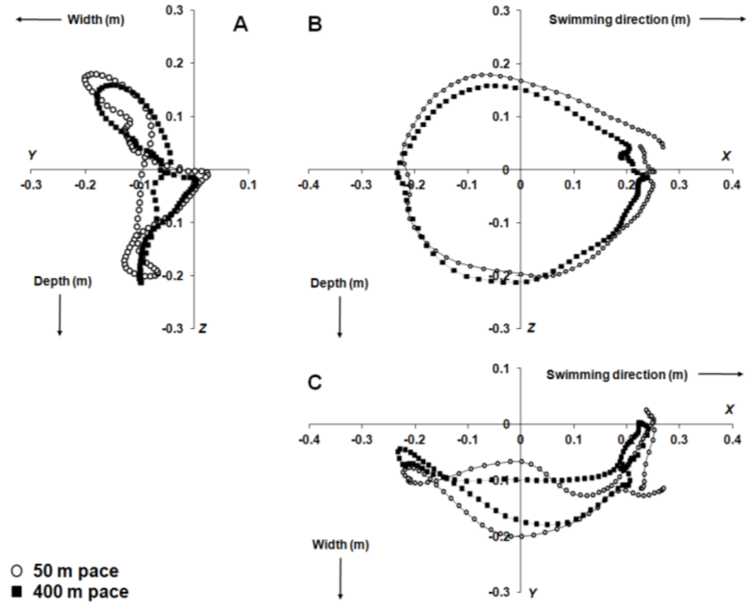

Figure VI. 8 Participant 3 (♂): Unaffected-elbow trajectory, front (A), side (B), above (C) views.

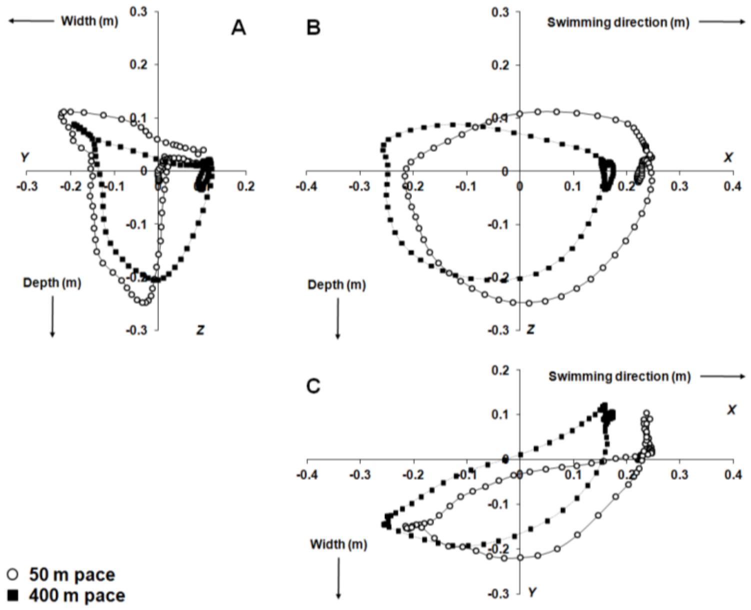

Figure VI.9 Participant 3 (♂): Affected-elbow trajectory, front (A), side (B), above (C) views.

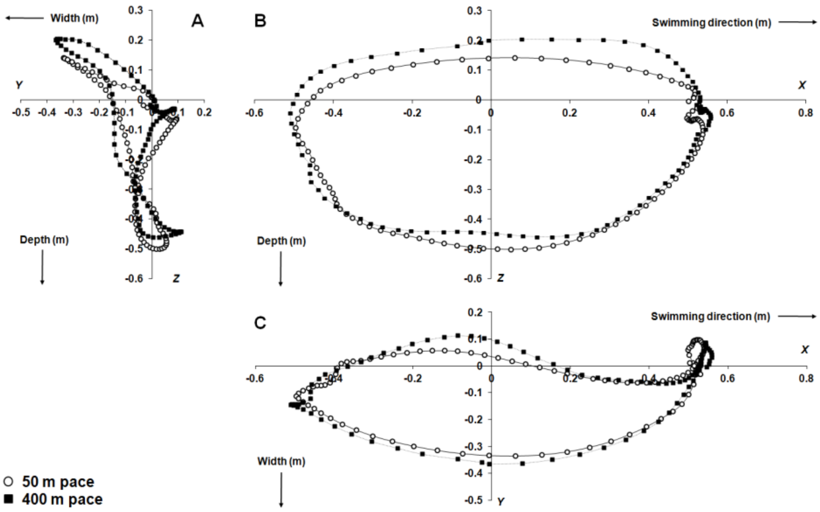

Figure VI. 10 Participant 4 (♂): Right hand trajectory, front (A), side (B), above (C) views.

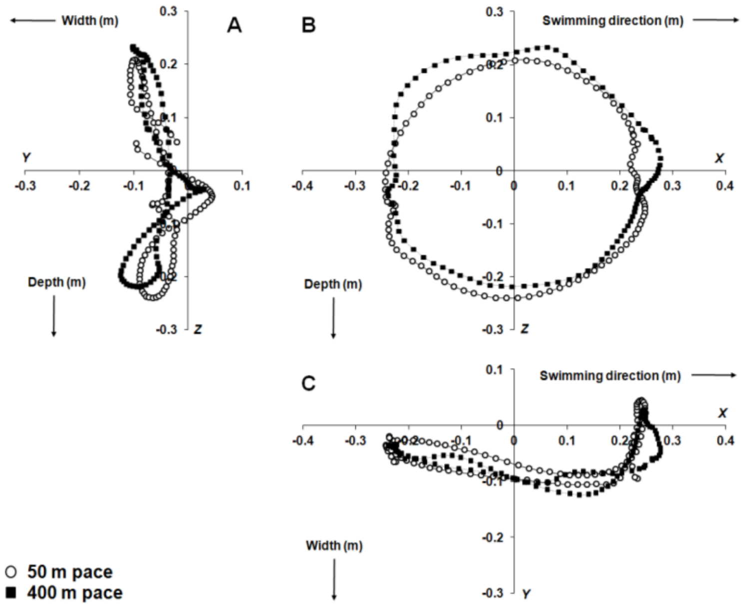

Figure VI. 11 Participant 4 (♂): Unaffected-elbow trajectory, front (A), side (B), above (C) views.

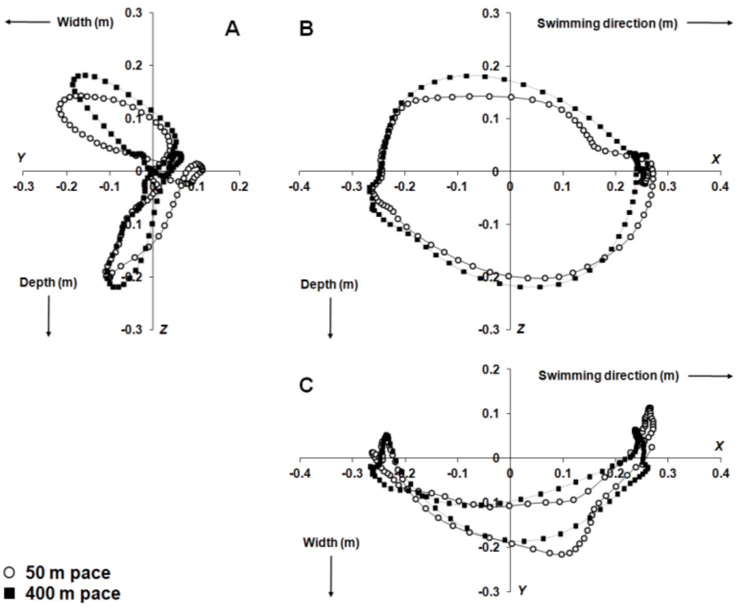

Figure VI.12 Participant 4 (♂): Affected-elbow trajectory, front (A), side (B), above (C) views.

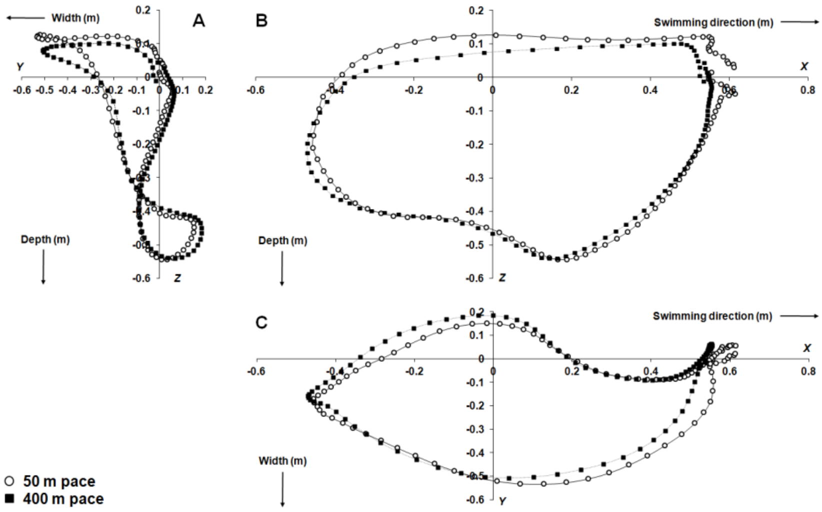

Figure VI. 13 Participant 5 (♂): Right hand trajectory, front (A), side (B), above (C) views.

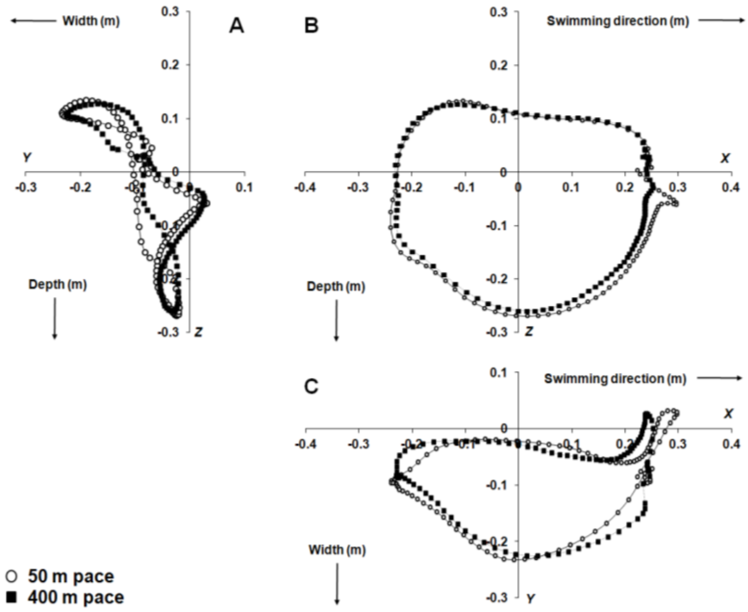

Figure VI. 14 Participant 5 (♂): Unaffected-elbow trajectory, front (A), side (B), above (C) views.

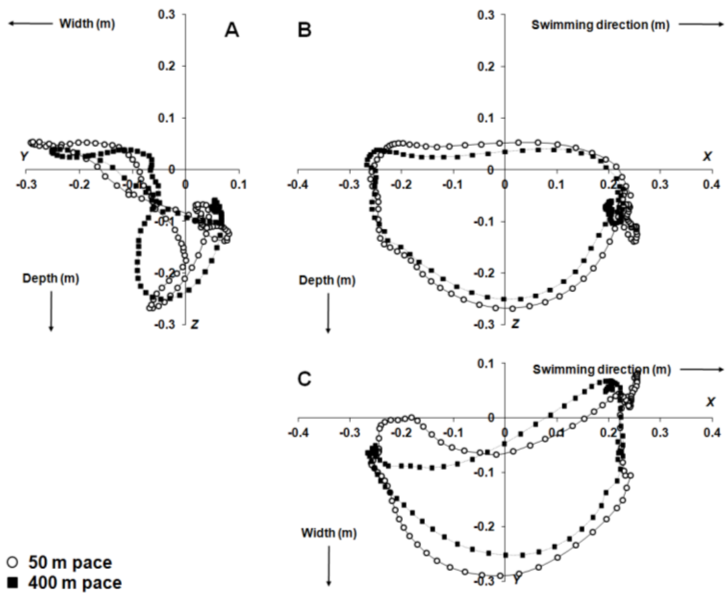

Figure VI.15 Participant 5 (♂): Affected-elbow trajectory, front (A), side (B), above (C) views.

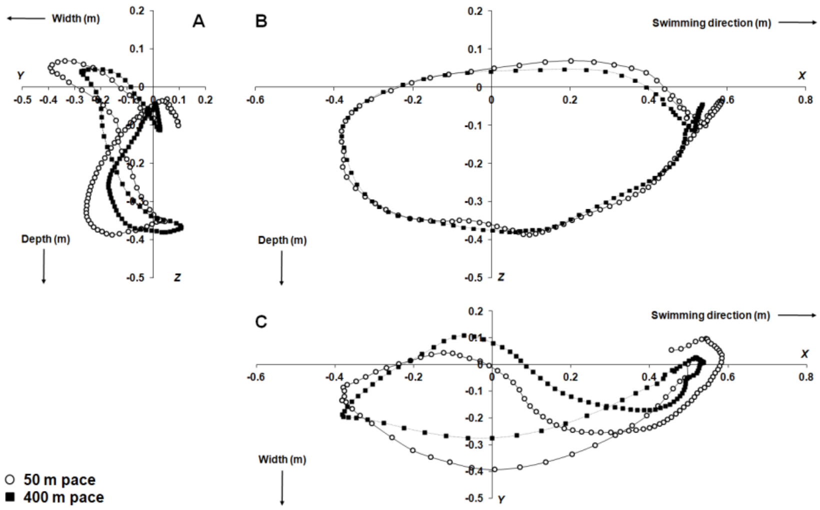

Figure VI. 16 Participant 6 (♂): Right hand trajectory, front (A), side (B), above (C) views.

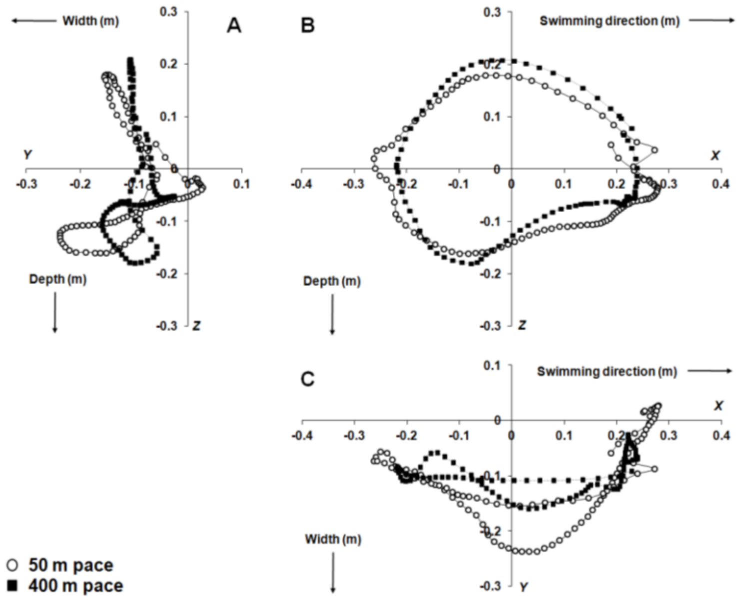

Figure VI. 17 Participant 6 (♂): Unaffected-elbow trajectory, front (A), side (B), above (C) views.

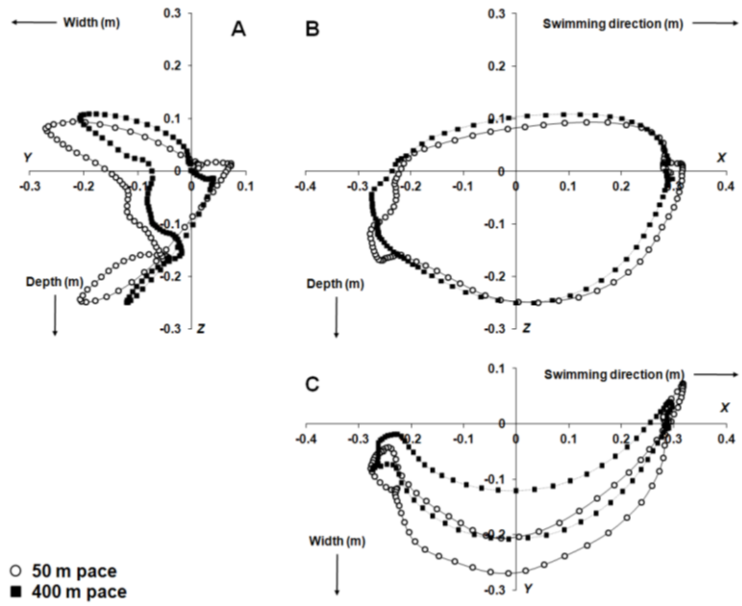

Figure VI.18 Participant 6 (♂): Affected-elbow trajectory, front (A), side (B), above (C) views.

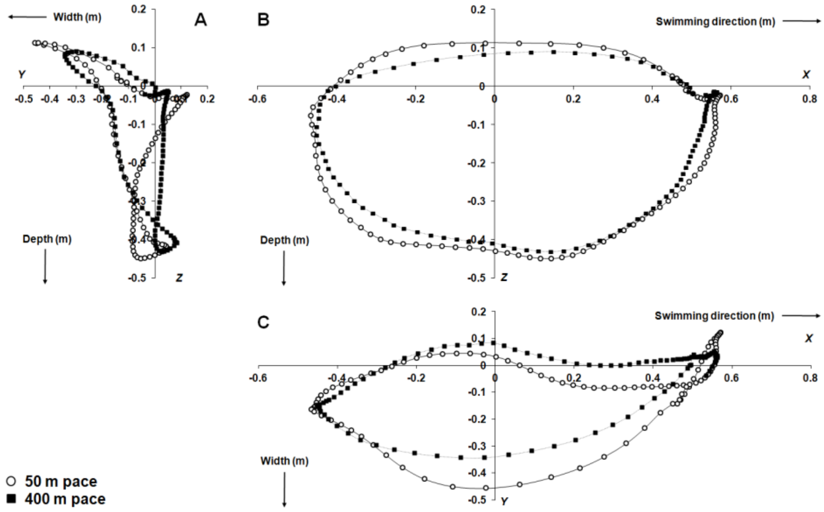

Figure VI. 19 Participant 7 (♂): Right hand trajectory, front (A), side (B), above (C) views.

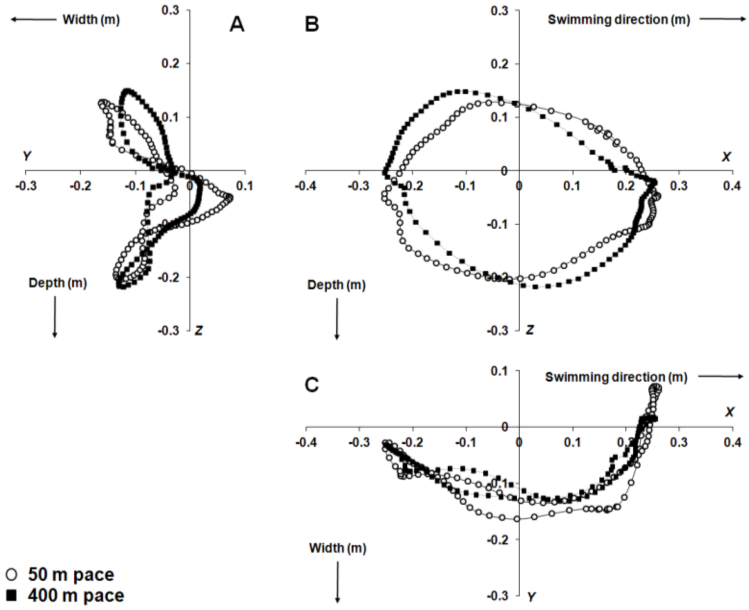

Figure VI. 20 Participant 7 (♂): Unaffected-elbow trajectory, front (A), side (B), above (C) views.

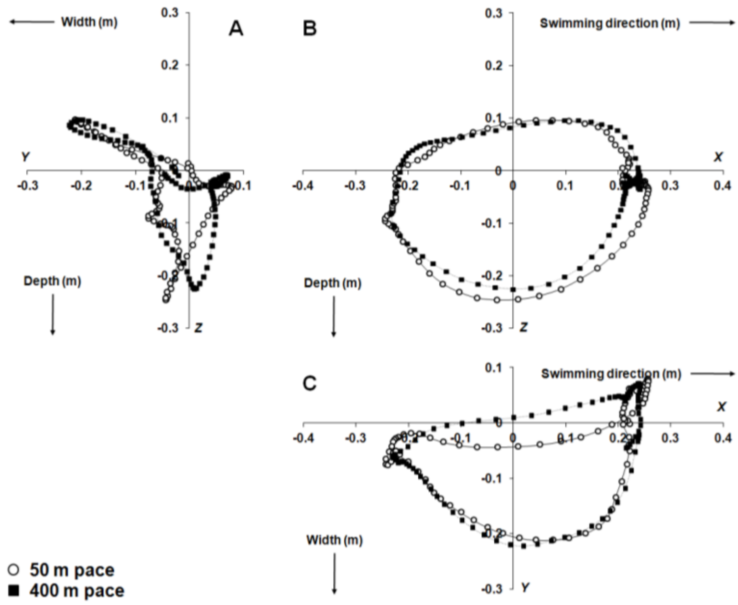

Figure VI.21 Participant 7 (♂): Affected-elbow trajectory, front (A), side (B), above (C) views.

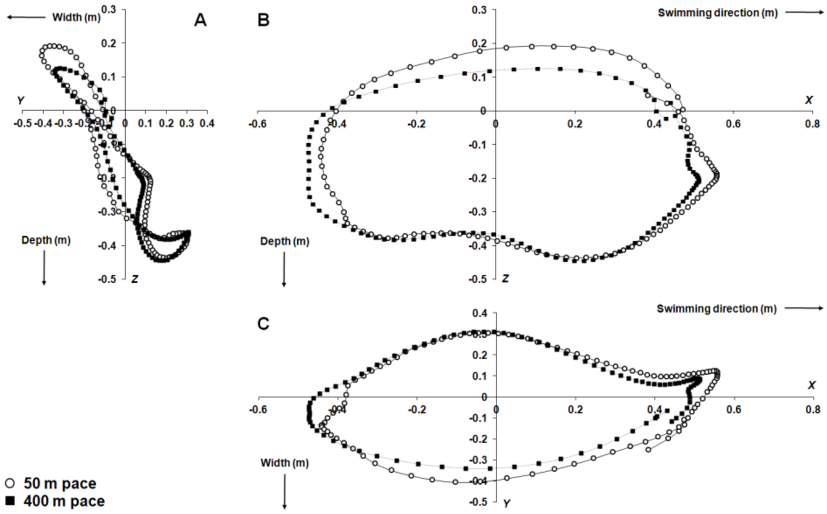

Figure VI. 22 Participant 8 (♂): Right hand trajectory, front (A), side (B), above (C) views.

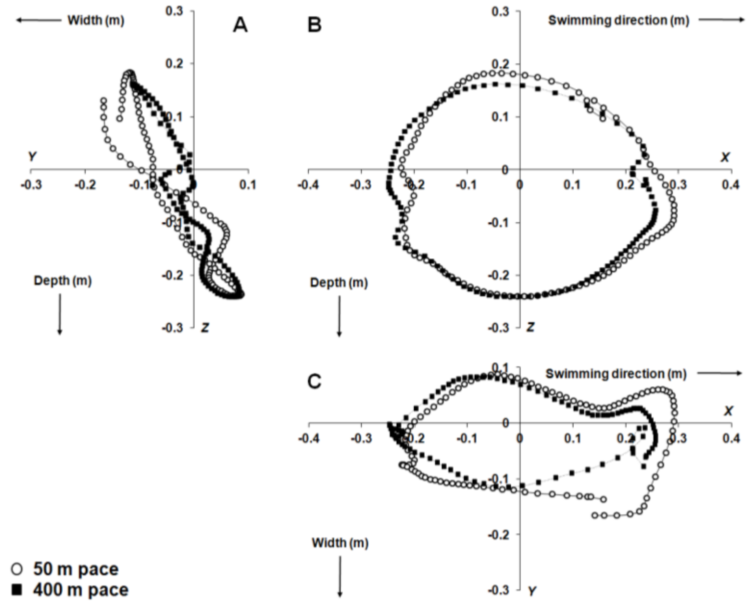

Figure VI. 22 Participant 8 (♂): Unaffected-elbow trajectory, front (A), side (B), above (C) views.

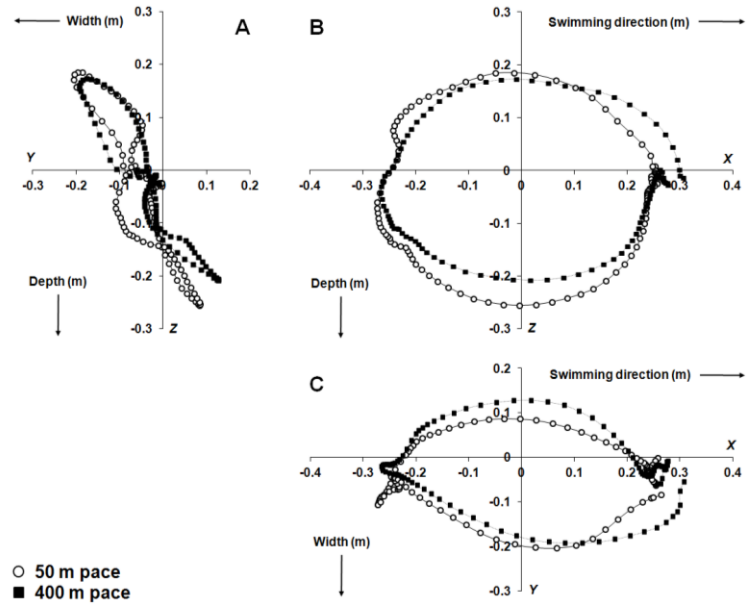

Figure VI.24 Participant 8 (♂): Affected-elbow trajectory, front (A), side (B), above (C) views.

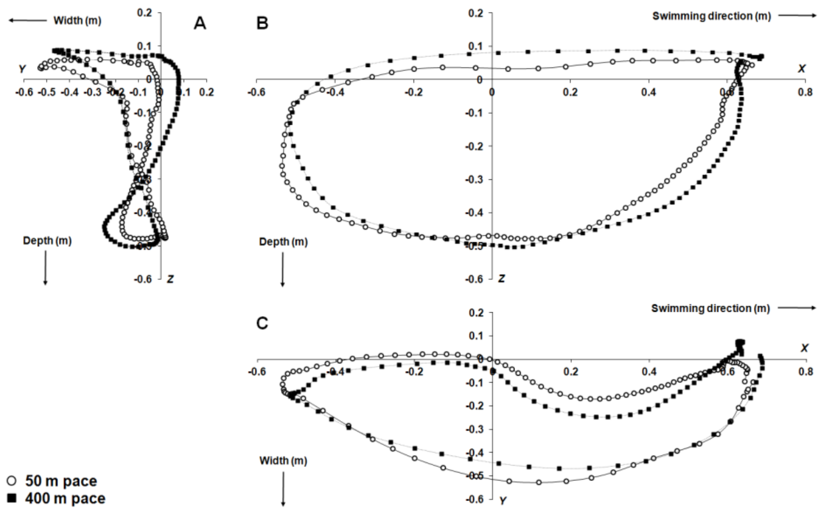

Figure VI. 25 Participant 9 (♀): Right hand trajectory, front (A), side (B), above (C) views.

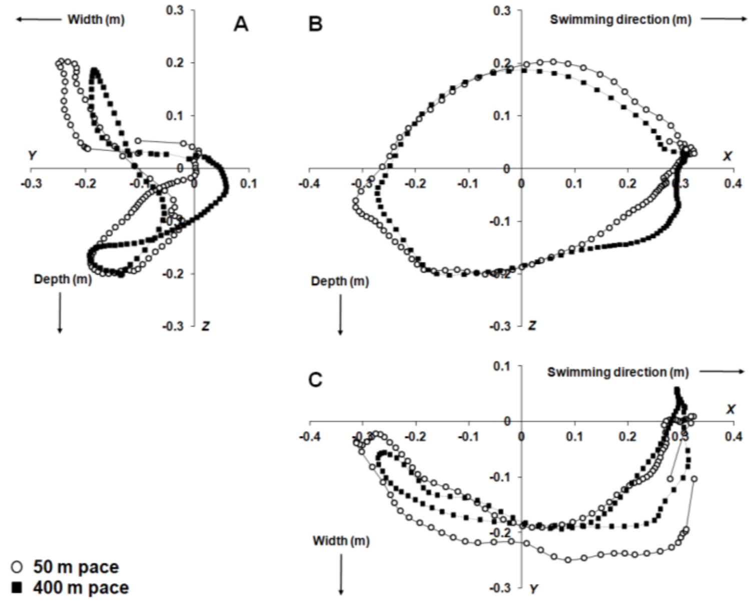

Figure VI. 26 Participant 9 (♀): Unaffected-elbow trajectory, front (A), side (B), above (C) views.

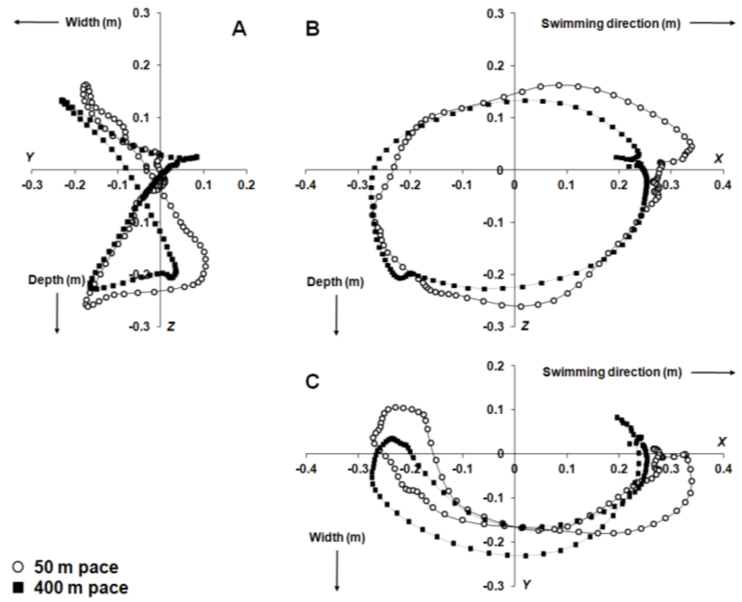

Figure VI.27 Participant 9 (♀): Affected-elbow trajectory, front (A), side (B), above (C) views.

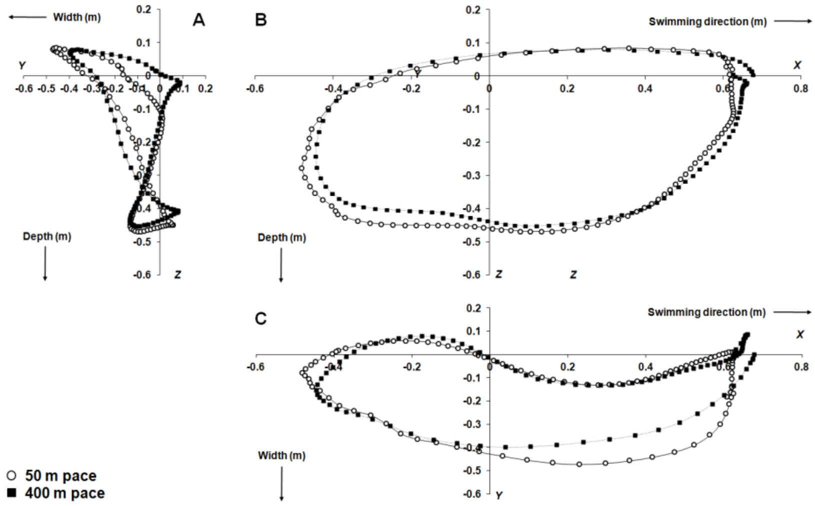

Figure VI. 28 Participant 10 (♀): Right hand trajectory, front (A), side (B), above (C) views

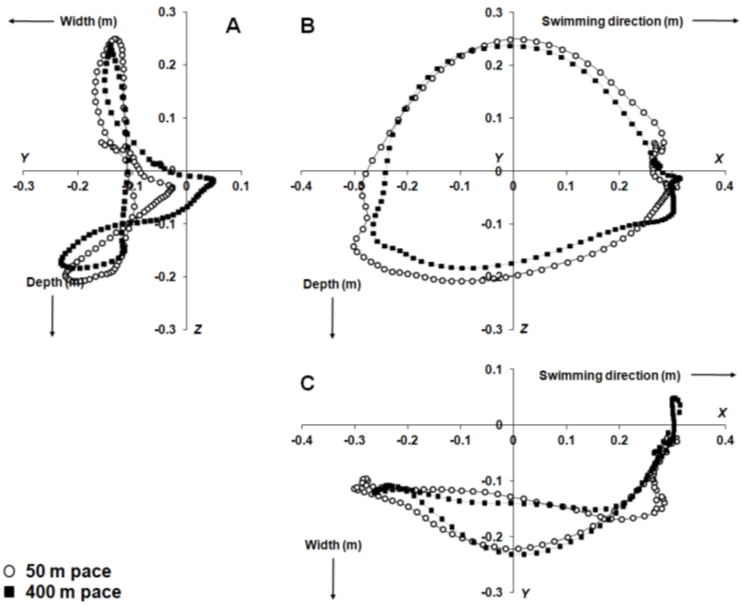

Figure VI. 28 Participant 10 (♀): Unaffected-elbow trajectory, front (A), side (B), above (C) view

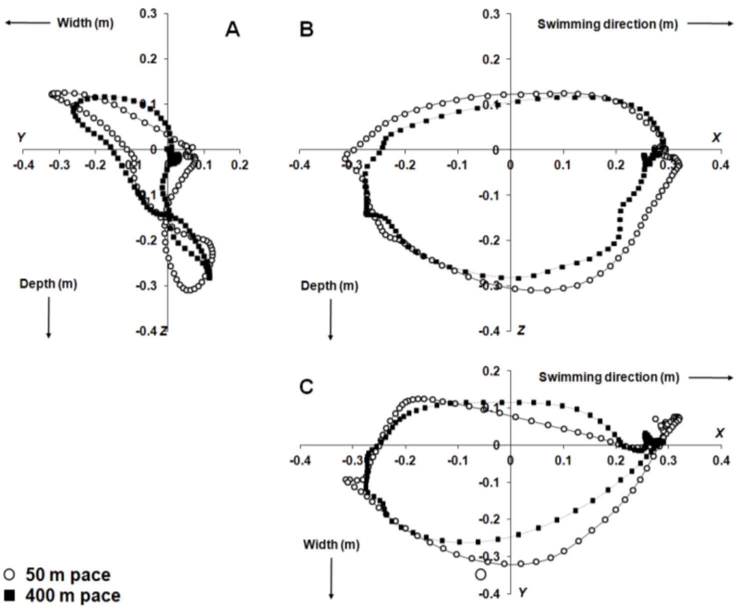

Figure VI.30 Participant 10 (♀): Affected-elbow trajectory, front (A), side (B), above (C) views.

APPENDIX VI

DETERMINATION OF INTRA- AND INTER-TESTER REPEATABILITY COEFFICIENTS AND ROOT MEAN SQUARE DIFFERENCES

Table VI a. Determination of inter- and intra-tester repeatability coefficients.

	Pull depth (m)	Pull width (m)	Pull length (m)	Pull Down vel. (m/s)	Pull Out vel. (m/s)	Push Up vel. (m/s)	Push In vel. (m/s)	Shoulder Roll 1 (°)	Shoulder Roll 2 (°)	Shoulder Roll 3 (°)	Shoulder Roll 4 (°)
Intra-tester	0.68	0.25	0.35	1.50	1.18	1.67	0.28	34	21	38	42
Inter-tester	0.67	0.25	0.34	1.56	1.29	1.73	0.32	32	23	38	41
Trial 1	0.668	0.254	0.340	1.495	1.288	1.692	0.317	30.702	20.402	36.923	41.661
Trial 2	0.665	0.257	0.338	1.559	1.238	1.751	0.291	30.371	19.991	38.196	42.380
Trial 3	0.672	0.245	0.336	1.526	1.144	1.750	0.292	31.513	23.083	38.483	41.708
Trial 4	0.671	0.252	0.346	1.569	1.239	1.727	0.309	30.842	21.455	37.028	41.625
Trial 5	0.667	0.246	0.339	1.531	1.226	1.744	0.297	31.062	22.648	37.124	41.154
Intra-diff 1	0.01	-0.01	0.01	0.00	-0.11	-0.02	-0.04	3.50	0.91	0.84	-0.08
Intra-diff 2	0.01	-0.01	0.01	-0.06	-0.06	-0.08	-0.01	3.83	1.32	-0.43	-0.80
Intra-diff 3	0.00	0.00	0.01	-0.03	0.03	-0.08	-0.01	2.69	-1.77	-0.72	-0.13
Intra-diff 4	0.00	-0.01	0.00	-0.07	-0.06	-0.06	-0.03	3.36	-0.14	0.74	-0.04
Intra-diff 5	0.01	0.00	0.01	-0.03	-0.05	-0.07	-0.02	3.14	-1.33	0.64	0.43
95% Limit	0.01	0.01	0.01	0.06	0.10	0.05	0.02	1	3	1	1
Intra-tester coefficient			***0.008***				***0.06***				***1.4***
Inter-diff 1	0.00	-0.01	0.00	0.060	0.004	0.042	-0.002	1.32	2.08	0.77	-0.21
Inter-diff 2	0.00	-0.01	0.00	-0.004	0.054	-0.017	0.024	1.65	2.89	-0.50	-0.93
Inter-diff 3	-0.01	0.00	0.00	0.029	0.084	-0.016	0.023	0.50	0.39	-0.79	-0.26
Inter-diff 4	-0.01	-0.01	-0.01	-0.014	0.053	0.007	0.006	1.18	2.02	0.67	-0.17
Inter-diff 5	0.00	0.00	0.00	0.024	0.066	-0.010	0.018	0.96	0.83	0.57	0.30
95% Limit	0.01	0.01	0.01	0.06	0.06	0.05	0.02	1	2	1	1
Inter-tester coefficient			***0.007***				***0.05***				***1.3***

Table VI b. Determination of inter- and intra-tester root mean square differences.

	Pull depth (m)	Pull width (m)	Pull length (m)	Pull Down vel. (m/s)	Pull Out vel. (m/s)	Push Up vel. (m/s)	Push In vel. (m/s)	Shoulder Roll 1 (°)	Shoulder Roll 2 (°)	Shoulder Roll 3 (°)	Shoulder Roll 4 (°)
Intra-tester	0.68	0.25	0.35	1.50	1.18	1.67	0.28	34	21	38	42
Inter-tester	0.67	0.25	0.34	1.56	1.29	1.73	0.32	32	23	38	41
Trial 1	0.668	0.254	0.340	1.495	1.288	1.692	0.317	30.702	20.402	36.923	41.661
Trial 2	0.665	0.257	0.338	1.559	1.238	1.751	0.291	30.371	19.991	38.196	42.380
Trial 3	0.672	0.245	0.336	1.526	1.144	1.750	0.292	31.513	23.083	38.483	41.708
Trial 4	0.671	0.252	0.346	1.569	1.239	1.727	0.309	30.842	21.455	37.028	41.625
Trial 5	0.667	0.246	0.339	1.531	1.226	1.744	0.297	31.062	22.648	37.124	41.154
Intra-diff Sq. 1	0.0000	0.0001	0.0001	0.000004	0.01277	0.00044	0.00123	12.22202	0.83174	0.70896	0.00640
Intra-diff Sq. 2	0.0001	0.0001	0.0001	0.003844	0.00397	0.00640	0.00008	14.64593	1.75033	0.18576	0.63840
Intra-diff Sq. 3	0.0000	0.0000	0.0002	0.000841	0.00096	0.00624	0.00010	7.20922	3.12936	0.51552	0.01613
Intra-diff Sq. 4	0.0000	0.0000	0.0000	0.005184	0.00410	0.00314	0.00073	11.26274	0.01988	0.54317	0.00194
Intra-diff Sq. 5	0.0001	0.0000	0.0001	0.001156	0.00260	0.00533	0.00023	9.83450	1.77956	0.41088	0.18233
Mean squared difference			0.00007				0.00399				3.29474
Intra-tester R.M.S. difference			***0.009***				***0.06***				***1.8***
Inter-diff Sq. 1	0.00000	0.00005	0.00000	0.003600	0.00002	0.00176	0.00000	1.729225	4.305625	0.597529	0.043681
Inter-diff Sq. 2	0.00000	0.00008	0.00000	0.000016	0.00292	0.00029	0.00058	2.709316	8.328996	0.250000	0.861184
Inter-diff Sq. 3	0.00004	0.00000	0.00000	0.000841	0.00706	0.00026	0.00053	0.254016	0.155236	0.619369	0.065536
Inter-diff Sq. 4	0.00003	0.00003	0.00004	0.000196	0.00281	0.00005	0.00004	1.380625	4.088484	0.446224	0.029929
Inter-diff Sq. 5	0.00000	0.00000	0.00000	0.000576	0.00436	0.00010	0.00032	0.912025	0.687241	0.327184	0.088804
Mean squared difference			0.00002				0.00141				1.394011
Inter-tester R.M.S. difference			***0.004***				***0.04***				***1.2***