UNDERWATER KICKING FOLLOWING THE FREESTYLE TUMBLE TURN

By

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B. App. Sci. (Human Movement) (Hons.)

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List of Abbreviations

2D	Two dimensional
3D	Three dimensional
ANOVA	Analysis of Variance
ANOCOVA	Analysis of Covariance
C_D	Coefficient of drag
CG	Centre of gravity
CM	Centre of mass
CM_{global}	Whole body centre of mass
EMG	Electromyography
FINA	The Federation Internationale de Natation Amateur
Re	Reynolds number
RTT	Round trip time
RTTs	Round trip times
SD	Standard deviation
SEM	Standard error of the mean
UUS	Underwater undulatory swimming
Vmax	Maximum velocity
VO_2	Oxygen consumption
WCT	Wall contact time
WCTs	Wall contact times

Abstract

Swim turns are a component of competitive swimming where considerable advantage can be gained or lost. This thesis investigates underwater dolphin and flutter kicking techniques and their application to exits following the turn in freestyle swimming. Five separate investigations were conducted to examine the kinetics and kinematics of each underwater kicking technique and are presented in expanded journal manuscript form. Studies one, two and three involved the comparison of freestyle turns when using flutter and dolphin kicking wall exit techniques. The results obtained indicated that freestyle turns using flutter kicking were faster than dolphin kicking in age-group swimmers. For this group, significant and equal improvements were made to flutter and dolphin kick turn performances following six weeks of dolphin kick and dolphin kick turn training. However, no difference in turn times were observed between kicking conditions by older and more highly skilled swimmers. Study four involved a kinematical comparison of maximal underwater free-swimming dolphin and flutter kicking. Results showed dolphin kick to be a superior underwater free-swimming technique. Greater foot width, increased ankle range of movement and greater vertical displacement of the ankle and foot during kicking were shown to be highly predictive of faster underwater dolphin kicking. Investigation five compared the drag forces and kinematics between the dolphin and flutter kicking techniques while subjects were towed at velocities representing those experienced following wall turn push-off. Results favour the dolphin kick as a superior underwater technique at these higher velocities. Increased underwater dolphin kicking efficiency, as measured by decreased net towing force, was found to be associated with larger kick amplitude – rate ratios, and higher kick amplitude – streamline length ratios.

Statement of Authorship

I, Peter James Clothier, hereby declare that except where explicit reference is made in the text of the thesis, this thesis contains no material published elsewhere or extracted in whole or in part from a thesis by which I have qualified for or been awarded another degree or diploma. No other person's work has been relied upon or used without due acknowledgment in the main text and bibliography of the thesis.

This research was conducted under the supervision of Professor Warren Payne, Professor Brian Blanksby and Mr Keith McElroy.

This thesis has been prepared to conform to the guidelines provided by The University of Ballarat (Part B: The degree of Doctor of Philosophy, Regulation 5.1, pp. 7-9) and is based upon the style recommended in the Publications Manual of the American Psychological Association (5th edition: 2003). Spelling is Australian English.

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Peter James Clothier

CANDIDATE

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Underwater Kicking Following the Freestyle Tumble Turn

Chapter 1

Introduction

Background

The modern era of swimming demonstrates such evenness in performance that many of the swimmers competing in a final have a realistic chance of winning. Consequently, coaches and their swimmers spend hours training and exploring techniques to swim faster. Until recently, the pursuit of swimming excellence has placed greater emphasis on improving stroke mechanics and physiological development with relatively little importance placed on turns and turning technique.

The time it takes to complete an event is the ultimate measure of a swimmer's performance (Hay, 1987). Total swim time can be considered the sum of the times taken starting, stroking and turning and determines whether a swimmer will win or lose a race (Hay, Guimaraes & Grimston, 1983). Gains or losses in either of these three race components can therefore significantly affect a swimmer's performance. Turning has been shown to comprise approximately 20 %, and up to 36 %, of total race time, depending on race length, during freestyle events in short course pools (Thayer & Hay, 1984). Moreover, turning time has been shown to correlate positively with final event time (Chow, Hay, Wilson & Imel, 1984). Maglischo (1993) stated that improved turns could decrease sprint race times by at least 0.2 s per length with the possibility of even greater decreases in swim times in longer races due to the greater number of turns involved. A long-course 1500 m freestyle race consists of one start and 29 turns. Time gains of 0.2 s per turn could therefore equate to a significant reduction of 5.8 s in total race time for this event.

Despite the relative importance of turns in the overall performance for competitive swimming, relatively few studies have addressed the techniques used in turning. Hay (1988) cited the absence of simple, convenient and versatile methods for studying turning techniques as the cause for the limited number of such studies. Of the 152 papers published in the proceedings of the first four International Symposia on the Biomechanics of Swimming, only two were devoted to the topic of turns (Hay, 1988). Until recently, the paucity of turn research has led to swimming turns being developed predominantly through intuition, experience, and trial and error adjustments to existing techniques. This can be evidenced by the volume of varying instructional literature on swimming turns that has been published by coaches over the years (Cox, 1981; Edson, 1988; Eggert, 1992; Freeney, 1993; Furniss, 1984; Hamlin, 1984; Hines, 1993; Rutemiller, 1995; Rutemiller & Whitten, 1996; Snowberger, 1988; Todd, 1988; Trembly, 1982; Trembly, 1983; Weber, 1976). Consequently, knowledge of the best method and the mechanics of performing the freestyle turn have evolved sporadically through time. However, technological advancements and new theoretical knowledge has impacted on the development of new techniques and allowed accurate scientific investigation of these technique innovations. These advancements, in combination with the necessity for swimmers to continually improve, suggest that ideal swim techniques are yet to be discovered and developed.

Early research on the performance of swimming turns typically focussed on comparison of the time taken to perform different turning motions (Fox, Bartels & Bowers, 1963; King & Irwin, 1957; Scharf & King, 1964). More recent investigations of swimming turns have incorporated wall kinetics by using force platforms as well as a greater variety of kinematic measures to examine turn performance (Blanksby, Gathercole & Marshall, 1996; Blanksby, Hodgkinson & Marshall, 1996; Blanksby, Simpson, Elliott & McElroy, 1998; Blanksby, Skender, Elliott, McElroy & Landers, 2004; Daniel, Klauck & Bieder, 2002; Gathercole, 1994; Hodgkinson, 1994; Hodgkinson & Blanksby, 1995; Lyttle, Blanksby, Elliott & Lloyd, 1999; Lyttle & Mason, 1997; Nicol & Kruger, 1979; Takahashi, Yoshida, Tsubakimoto & Miyashita, 1983). It is becoming clear from these investigations that several kinetic and kinematic parameters play critical roles in turn performance. Optimising the force applied to the wall, reducing drag during the streamlined glide and the utilisation of an effective underwater kick style and technique will lead to turn times being reduced. However, further turn kinetic and kinematic investigations are required to conclusively identify critical elements of freestyle turn performance.

Akin to technique improvements achieved in other sports, coach intuition and trial and error have been the main means used to derive many of the techniques currently used by competitive swimmers. This is further evidenced by the variation in turning techniques demonstrated by today's swimmers. One such variation is the use of an undulatory double-leg kicking action before the commencement of stroking, following the freestyle tumble turn. An increasingly common label used to describe this technique is 'dolphin kicking'. However, dolphin kicking has traditionally referred to the kick performed during butterfly swimming and is kinematically and kinetically very different to that used in freestyle and other stroke turns where the arms are not used. Although this naming duplication may bring about confusion among swimming circles, the term dolphin kicking is used throughout this thesis to refer to underwater undulatory double-leg kicking, unless stated otherwise.

Little doubt exists that for many swimmers, the underwater dolphin kick used in backstroke starts and turns has reduced race times. Despite the use of dolphin kicking following freestyle turns by some swimmers, debate exists regarding the effectiveness of this technique. Moreover, a modest amount of scientific research has been conducted to confirm whether this wall exit strategy is superior to the more traditional flutter kick.

Lyttle, Blanksby, Elliott and Lloyd (2000) investigated the merits of different underwater gliding and kicking techniques during tethered towing of 16 experienced adult male swimmers. No significant difference in net drag force between three underwater kicking techniques (prone freestyle, prone dolphin and lateral dolphin) was observed when towed at velocities between 1.6 and 3.1 $m.s^{-1}$. Despite a trend by many swimmers favouring the adoption of prone underwater dolphin kicking, the authors were forced to conclude that swimmers should adopt the technique at which they are most proficient when exiting the wall following a turn (Lyttle et al., 2000).

The only study conducted into free-swimming kicking to have previously compared flutter and dolphin kicking techniques was conducted by Sheeran (1980). This investigation used waterproofed electrogoniometers to examine the range of motion in the knee and ankle articulations of 14 male university level swimmers during performance of the front flutter, back flutter and dolphin kicking techniques. Results indicated dolphin kicking produced significantly ($p<0.05$) larger range and degree of maximum flexion of the knee than during flutter kicking. No significant differences were observed in the range of movement of the ankle despite the dolphin kicking trials producing a considerably larger range (13 %), and greater flexion and extension maximums (Sheeran, 1980). However, application of these findings to support the adoption of dolphin kicking turn exits is limited due to insufficient detail regarding the kicking velocity and kick position relative to the water surface (on or under).

In the pursuit of improved swimming performance, hydrodynamic theory and the results of aquatic animal research have been increasingly applied by sport biomechanists to human swimming. Pelagic fish research indicates that almost entirely regardless of shape and size, creation of an undulatory transverse wave that progresses along the body to the tail is the most effective swimming movement (Wu, 1971). The heaving and pitching of the body and caudal fin (tail fin) cause masses of water to be set into rotation such that specific wakes known as vortices are generated. The result from these movements and creation of vortices is a thrust that propels the animal forward horizontally (Triantafyllou & Triantafyllou, 1995; Ungerechts, Persyn & Colman, 1999; Videler, 1993). Research has shown that pelagic fish and dolphin swimming velocity increases with increased tail beat frequency (Jayne & Lauder, 1995; Ungerechts, Daly & Zhu, 1998). Furthermore, studies have shown that tail beat amplitudes do not exceed greater than 25 % of body length for dolphins (Ungerechts et al., 1998) and values approximating 20 % in other fish species (Hertel, 1966). These findings suggest optimal undulatory kick amplitudes and frequencies may exist for the production of maximal undulatory swimming velocity. Many aquatic animals are optimally designed for movement through water. Hence, more efficient human swimming techniques may be developed through the application of knowledge obtained from investigating their movements (Lyttle, 1999; Ungerechts et al., 1998). If humans are to adopt an undulatory swimming technique for part of an event then it is possible that optimal kicking amplitudes and frequencies may also exist.

It is noted that reference to and comparison between humans and certain aquatic species in this thesis are not intended to infer similar or identical aquatic movement relationships. Rather, it is proposed that comparison may identify possible mechanisms that may lead to improved human swimming techniques. Therefore, this thesis does not implicitly advocate humans adopt various aquatic specie movement patterns and that careful evaluation of this analogy should be exercised by the reader and swimming science in general.

The majority of previous undulatory kicking studies in humans have been conducted at the water surface or within butterfly swimming. Consequently, this limits the application of findings to underwater undulatory swimming (UUS). Also, there are relatively few investigations examining UUS kinematics in humans other than during fin-swimming. Arellano, Pardillo and Gavilan (2000) used a comparative approach to determine critical kinematic elements of UUS by examining the performance differences between international and national standard swimmers. Comparative analysis between the groups indicated that the international standard group performed UUS with significantly higher mean horizontal velocity, kick frequency, maximal knee flexion, and kick amplitude per horizontal distance (amplitude/horizontal displacement of the kick). Further, Arellano et al. (2000) found the percentage of kick amplitude relative to body height was 34.31 % and 36.58 % for the international and national groups, respectively. This indicates that the national standard group kicked with larger amplitude while swimming significantly slower. Correlation analysis within the international standard group revealed numerous significant relationships between the mean velocity of the centre of mass (CM) and several kinematic measures. In contrast, no relationship was found between the mean velocity of the CM and kick amplitude. This finding indicates that kick amplitude is unrelated to UUS velocity and contrasts with the findings from previous surface dolphin (Barthels & Adrian, 1971) and flutter kicking studies (Alley, 1952; Thrall, 1960).

Despite Arellano and co-workers (2000) identifying differences between groups of varied swimming ability and demonstrating significant relationships between the mean velocity of the CM and several kicking kinematic measures, the relative importance of individual kicking kinematic measures to kick velocity were not determined. Hence, further investigations incorporating regression analysis is required to determine the relative importance of various kinematic parameters to kicking velocity and thus, enable UUS techniques to be optimised.

In summary, the relative paucity of literature examining freestyle turns and underwater kicking presents both contrasting and inconclusive findings. Despite recent efforts by a small number of researchers, optimal underwater kicking style and technique when exiting the wall following turns in freestyle swimming has not been scientifically verified. In addition, no studies have attempted to examine and determine optimal underwater kicking kinematics in relation to wall exit following the turn. Investigations focussing on the kinetic and kinematic comparison of wall exit techniques will clarify the current confusion associated with varying freestyle turning techniques and assist coaches and swimmers pursue new levels in performance.

Statement of the problem

The purpose of the present work was to generate knowledge of underwater dolphin and flutter kicking techniques and their use during wall exit following the turn in freestyle swimming. This was undertaken by an applied, evolutionary approach that sought practical outcomes for application in coaching to improve swimming performance. More specifically, this series of studies sought to investigate and quantify the following sub-problems.

Study 1:

This study sought to compare the biomechanical and performance characteristics of a modified freestyle tumble turn which used a dolphin kick off the wall with the traditional freestyle turn that incorporates a flutter kick off the wall, in age-group swimmers. This population was chosen to provide a wider variety of performance scores in the hope that this would enable clearer identification of the areas contributing to good performance. The following sub-problems were examined in this investigation:

- Are levels of performance similar between a modified freestyle tumble turn which used a dolphin kick off the wall with the traditional freestyle turn that incorporates a flutter kick off the wall?
- Do turn measures preceding the kicking phase vary between dolphin and flutter kicking wall exit techniques?
- What are the performance measures that contribute to faster dolphin kick turns?

Study2:

The results of Study 1 revealed an unexpectedly superior flutter kicking ability and the inability of age-group swimmers to adapt quickly and with skill to the dolphin kick turn strategy. Subsequently, results showed the traditional flutter kick method of exiting from the freestyle turn to be significantly faster than turns with a dolphin kick exit. The observed difference in turn performances was considered most likely due to the swimmers possessing more mature flutter kicking movement patterns, rather than the effectiveness of each kicking strategy. For that reason, the following sub-problems were examined using age-group swimmers in this investigation:

- Does dolphin kicking and dolphin kicking turn practice improve dolphin kicking turn performance?
- Are levels of performance similar between dolphin kick and flutter kick turns following dolphin kicking and dolphin kicking turn practice?

Study3:

Studies 1 and 2 demonstrated that flutter kick exits from the wall contribute to significantly lower 5 m freestyle turn RTTs in age-group swimmers. This was evidenced both before and after specific dolphin kick training. However, large performance variation exhibited during these investigation limited accurate comparison of the two wall exit techniques. Hence, a replication of Study 1 using higher calibre swimmers was deemed necessary. The following sub-problems were therefore examined in this investigation:

- Are levels of performance similar between dolphin kick and flutter kick turns by high calibre swimmers?
- Do turn measures preceding the kicking phase vary between dolphin and flutter kicking wall exit techniques performed by high calibre swimmers?

Study4:

Study 3 demonstrated no difference in turn 5 m out-times between the dolphin and flutter kicking turn technique styles for high calibre swimmers. However, considerable advantages were observed for individual swimmers in relation to each turn technique style. With this observation, the aim of this investigation was to examine maximal free-swimming underwater kicking styles and to identify technique and anthropometric characteristics that are predictive of fast underwater kicking. Hence, the following sub-problems were examined using high calibre swimmers:

- Are levels of performance similar between maximal free-swimming underwater dolphin and flutter kicking?
- What performance measures are associated with fast underwater dolphin and flutter kicking?
- What anthropometric characteristics are associated with fast underwater dolphin and flutter kicking?
- What affect does modifying kick frequency and amplitude have on underwater dolphin kicking proficiency?

Study5:

Study 4 showed free-swimming underwater dolphin kick to be superior to that of flutter and two, unpractised modified dolphin-kicking techniques. However, maximal underwater free-swimming kicking velocity is lower than the velocities associated with wall push-off following the turn. Identification of key elements of efficient underwater kicking at those velocities experienced following the turn may serve to improve overall turn performance through appropriate underwater kick technique selection and / or improvement. Therefore, this investigation aimed to quantify differences in underwater kick styles and to identify technique and anthropometric characteristics that are predictive of efficient underwater kicking while towed at velocities representing those experienced during freestyle turn wall exits. Hence, this study examined the following sub-problems using high calibre swimmers:

- Are levels of performance similar between underwater dolphin and flutter kicking during towing at velocities representing those experienced during freestyle turn wall exits?
- What performance measures are associated with proficient underwater dolphin and flutter kicking at those velocities experienced during freestyle turn wall exits?
- Are anthropometric characteristics are associated with proficient underwater dolphin and flutter kicking at those velocities experienced during freestyle turn wall exits?

Delimitations

This thesis was delimited to the application of dolphin and flutter-kicking wall exits following freestyle tumble turns. The specific investigations into underwater dolphin and flutter kicking kinetics and kinematics were delimited to the lower extremity of the body. This project was also constrained to a biomechanical analysis without consideration of the physiology associated with the turns and underwater kicking techniques.

Limitations

The ability to generalise the findings of this work to the broader swimming community is limited to the subject populations analysed in each study. Similarly, the modest subject numbers in some studies limits interpretation of the statistical analyses with respect to statistical power.

Chapter 2

Literature Review

The focus of the thesis was to examine underwater kicking techniques and their application to exits following the freestyle turn, with the overall aim to improve freestyle turn performance. To achieve this, a review of relevant literature was conducted to explore the known factors that are likely to contribute to turn performance. Therefore, this literature review represents an overview of information relevant to the topic of consideration. In particular, this review focuses on previous freestyle turn research and appropriate aspects of swimming hydrodynamics. A secondary purpose of this review was to assist the development of procedures for the measurement of selected factors that may contribute to improved wall exit following the turn.

Freestyle turn definition

Any swimming race requiring the competitor to swim further than the pool length necessitates a change of direction. This act of changing direction in the water is known as a turn. Specific turn techniques exist for all the competitive strokes and medley stroke changes. The turn techniques currently used are not only considered generally the most efficient, but must comply with the rules of the stroke as set by FINA (The Federation Internationale de Natation Amateur), the international governing body of swimming. Freestyle swimming is simply that; free style. According to FINA, "Freestyle means that in a event so designated the swimmer may swim any style, except that in individual medley or medley relay events, freestyle means any style other than backstroke, breaststroke or butterfly" (FINA, 2002-2005, pp.118).

The variations seen between stroke definitions and rules are also seen in the rules governing the turns for each stroke. Generally, the nature of the stroke is incorporated into the turn. For example, breaststroke requires the hands to mirror each other while swimming. Not surprisingly, the breaststroke turn and finish require both hands to touch the wall simultaneously and symmetrically. Freestyle has no specific stroke rules; hence the action of turning during freestyle simply requires some part of the swimmer touching the wall upon completion of each length and at the finish (FINA, 2002-2005, pp.118). The FINA rules for freestyle swimming also state:

> Some part of the swimmer must break the surface of the water throughout the race, except it shall be permissible for the swimmer to be completely submerged during the turn and for a distance of not more than 15 metres after the start and each turn. By that point, the head must have broken the surface (FINA, 2002-2005, pp.118).

Therefore, the unrestricted nature of freestyle swimming allows for variation in turn techniques to exist and be developed.

Freestyle turn technique

While the most common freestyle turn technique used today is the tumble turn, this was not always the case. The rules of freestyle swimming once required all competitors to touch the wall using their hand prior to turning. This turn technique, known as the 'open turn', started with a rotation around the longitudinal axis of the body during the touch, followed by rotations around the transverse and frontal axes until a lateral body position for push off is achieved (Nicol & Kruger, 1979). Alteration to the freestyle turn rule saw the development and experimentation with the flip or tumble turn. According to Ward (1976), the flip/tumble turn for freestyle was first used in competition during 1936 due to a change in the rules of swimming. Nicol and Kruger (1979) describe this tumbling action as movement around of the body around a nearly horizontal transverse axis, followed by a twisting rotation around the longitudinal axis of the body after the push off.

Execution of a tumble turn requires a swimmer complete a series of complex movements to allow them to change direction. Descriptions of tumble turn technique and performance are found to vary slightly within the literature. Costill, Maglischo and Richardson (1992) describe the process of performing a flip/tumble turn using five separate movement phases. These phases will be used for the purpose of explanation within this review. Note also, that the following explanation is a description only with no attempt made to illustrate optimal turn performance at this time. The five turn phases are the approach; the turn; the push-off; the glide; and the pull-out. The approach to the turn refers the final stroke/s and the preparing of body position for the turn. Maintaining swim velocity is considered an important component of the approach to the turn.

According to Costill et al. (1992), the turn phase incorporates the somersault change of direction movement. To achieve this, the swimmer keeps the opposite arm in the water at the hip when beginning the final arm stroke. Forward rotation of the body is initiated by flexion of the head and a simultaneous small dolphin kick, during the final arm stroke. The legs are drawn to the chest by flexing the hips and knees. This movement causes a decrease in the moment of inertia around the axis of rotation, allowing the swimmer to somersault more easily. It is desirable for the arms to be in an extended position at the completion of the flip in preparation for good streamlining during the push-off. The swimmer should also execute a slight twist by turning the head to the side during the second half of the somersault. This allows the feet to be planted on the wall with the toes facing out and up in the same direction as the swimmers' body.

The push-off phase involves foot contact with the wall, leg extension and the exit from the wall. Costill et al. (1992) suggest the swimmer rotate towards a prone position while extending the legs powerfully. The push-off should be made horizontally and is completed by using the legs to rotate the body into a prone position after wall contact is lost. The glide phase involves the swimmer maintaining a streamlined position until race-swimming velocity is approached. Several kicks may be employed at this time after which the swimmer is ready to pull the head up through the surface using the first arm stroke. The first arm stroke designates the beginning of the final turn phase, the pull-out. This arm stroke should be half completed when the head breaks through the water surface, after which normal swimming can be resumed. The freestyle turn description above is derived from one of many that can be obtained from the literature or coaching manuals. Similarly, freestyle turns can be described and explained from a mechanical perspective. Figure 2.1 represents a theoretical model of the mechanical factors considered to contribute to freestyle turn performance (Lyttle, 1999). From this model it can be seen that average velocity out from the wall can play an important role in overall turn performance. The free nature of freestyle swimming permits the adoption of any swim style or modification. Therefore, the wall exit phase represents one area of turn performance where improvements could be made.

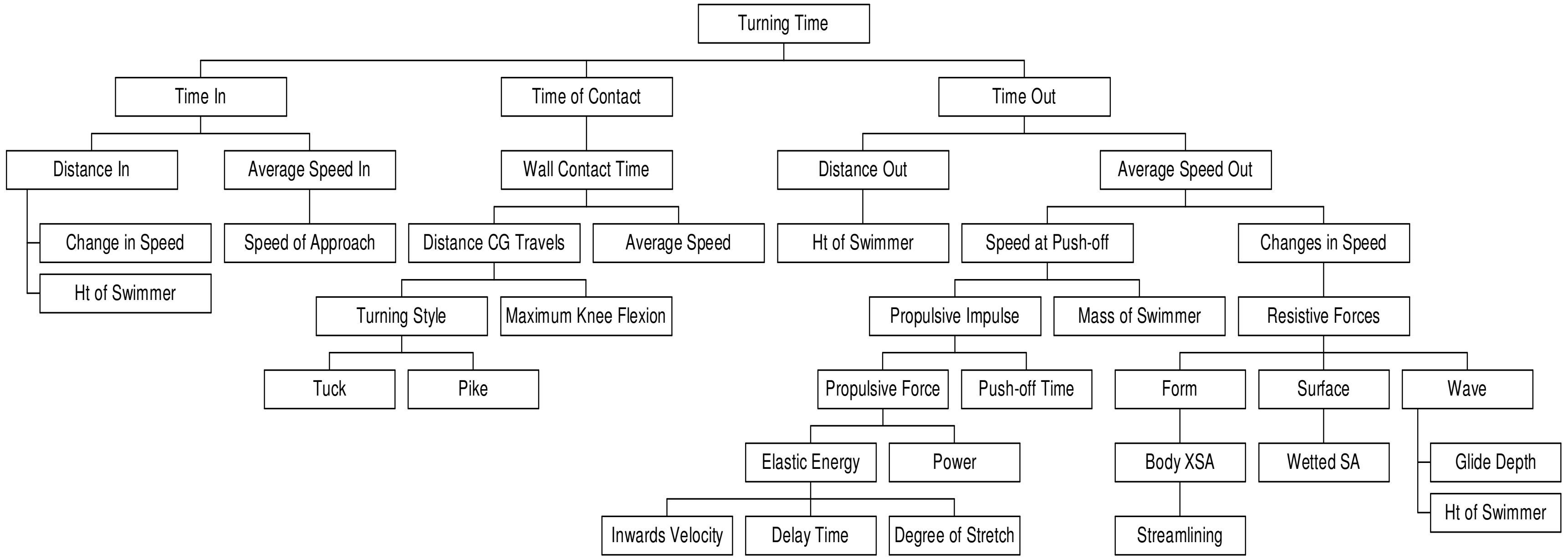

Figure 2.1. Contributing factors in a tumble turn.

Note 1. Ht = Height; XSA = Cross-sectional area; SA = Surface area

Note 2. Reprinted with permission from Lyttle (1999); originally adapted from Hay's (1992) model of turning and modified from Gathercole (1995).

Measurement of turn performance

Appropriate definition and measurement is necessary to accurately quantify swim turn performance. Methods of defining, and subsequently quantifying, turn performance vary within the literature. Interpretation differences in the commencement and completion of the turn bring about this variation. The timing of the arm stroke has been used to represent the turn in some studies (Chow et al., 1984; Hay et al., 1983). Using this method, Chow et al. (1984) defined commencement of the turn as the horizontal distance between the vertex of the head of the swimmer and the wall at the instant of last hand entry before initiating the turn. Similarly, turn completion was defined as the horizontal distance between the vertex of the head of the swimmer and the wall, at the instant of first hand entry during the first stroke after turning. This approach was believed to have a greater practical relevance as performances could be recorded from an above water position as viewed by spectators (Chow et al., 1984).

Arbitrary distances have also been used to define turn commencement and completion (Blanksby et al., 1998; Blanksby, Gathercole et al., 1996; Blanksby, Hodgkinson et al., 1996; Fox et al., 1963; King & Irwin, 1957; Lyttle et al., 1999; Lyttle & Mason, 1997; Newble, 1982; Scharf & King, 1964; Takahashi, Sakata, Tsubakimoto & Ae, 1983; Thayer & Hay, 1984). Early studies (King & Irwin, 1957; Scharf & King, 1964) defined turn commencement as the moment the swimmer’s hand touched the wall (once a rule requirement) and turn completion as the instant the swimmer’s hand reached a mark located 5 yd (4.57 m) from the wall. Fox et al. (1963) however, considered a freestyle turn to commence 3 ft 10 in (1.17 m) from the wall and end as the feet left the wall. More recently, turns have been defined as pre-determined distances in and out from the wall. Several fixed distances ranging from 3 m in to 6.5 m (Thayer & Hay, 1984) to 7.5 m in until 7.5 m out (Lyttle & Mason, 1997) have been employed and reported in relation to turn analysis. An important consideration in determining the fixed distances when defining the turn is whether these distances encompass all of the turn movement phases.

The 7.5 m in until 7.5 m out distances adopted by Lyttle and Mason (1997) were employed to encompass the turn preparation, rotation, gliding and stroke preparation phases of the turn. However, it is likely that fixed distances that are too large may encompass larger amounts of stroke swimming and do not accurately reflect turning performance. Conversely, fixed distances that are too small may not completely encapsulate the results emanating from the time spent on the wall (Blanksby, Gathercole et al., 1996). Although 2.5 m in and 2.5 m out distances would most closely incorporate the turning motion, measures such as peak wall exit velocity, swim resumption distance and velocity could not be obtained when this distance is used. Blanksby, Gathercole et al. (1996) suggest 5 m in and 5 m out are convenient distances over which to study turns. Also, coaches can time swimmers as they pass the backstroke flags inwards and outwards from the wall as these are located 5 m from the wall of the pool. Turn technique changes could therefore be made and assessed using time comparisons for this 5 m round trip time (RTT). Several other turn investigations have also favoured 5 m RTT as a criterion definition of turn performance (Blanksby, Gathercole et al., 1996; Blanksby et al., 1998; Blanksby et al., 2004; Lyttle et al., 1999; Newble, 1982; Takahashi & Sakata et al., 1983).

Although the use of arm stroke timing to define turn performance may provide a specific measure of a swimmer's individual turn, comparisons between swimmers is limited due to individual variations in turning distances that result from different turn initiation and stroke resumption distances (Lyttle, 1999). Conversely, the use of fixed and rationally chosen distances to define turn performance enables direct comparison between swimmers to be made. Therefore, fixed distances appear to be the most objective measures of turn performance and well suited for use in comparing variations in turn techniques.

Irrespective of the method used for objectively defining turn performance, early turn research relied almost exclusively on the time taken to complete whole turning motions as the criterion measure of performance (Fox et al., 1963; King & Irwin, 1957; Scharf & King, 1964). Fox et al. (1963) investigated the open and closed freestyle turn by comparing total turn time and the energy expenditure for each. The performances of six male subjects were examined to determine the relationship between both turns and to ascertain which was faster and more energy efficient. The closed turn was found to be significantly faster despite no significant difference in the energy cost between the two turns being observed. The crude measurement methods utilised in these early investigations (hand held stopwatches and tape measures) was quickly superseded with the introduction of cinematography and more recently, videography. The introduction of these forms of measurement resulted in an increase in the accuracy of turn performance measurement.

Much of the early turn research was focussed on comparison of different turning techniques. Schiessel (1966), as cited in Ward (1976), is reported to be the first research investigating freestyle flip turns. Schiessel (1966) reported results that favoured the pike turn as a superior flip turn technique. Assessment of the validity and reliability of Schiessel's work remains questionable, as the experimental design and methodology employed were not published. Despite the findings of Schiessel (1966), Ward (1976) saw reason to further investigate the pike and tuck variations of turning.

Ward (1976) conducted a cinematographical comparison of the pike (legs extended) and tucked (legs bent) freestyle turns using flip turn novices to determine which was the faster method. Fourteen subjects were selected and matched according to sex, body size, swim speed and subjective turn ability, and then divided into pike and tuck turn groups. Each group was instructed in each turn technique for a total of ten sessions each lasting 10 - 15 minutes in duration. Filming involved each pair of swimmers alternating the performance of their turn until ten trials each were completed. Time taken for the swimmer's head to pass a vertical plane while approaching the wall until the feet contacted the wall (time in), and the time from initial wall contact to the head passing the vertical plane while exiting the turn (time out) were measured from the film. Total turn time was computed from the summation of time-in and time-out. Statistical analysis revealed that the tuck turn was significantly faster than the pike turn, for time-in, time-out and total turn time. The findings of Ward (1976) directly contrasted with the results presented by Schiessel (1966). Ward (1976) stated however, that highly skilled swimmers, trained in each turn, may prove contrary to his findings and warranted further investigation.

The research of Adler (1979) focussed on the exit phase of the flip turn by comparing the one-arm pull with double arm pulls out (as in butterfly) from the turn. Fifty club swimmers aged 10 - 16 years were tested over 30 feet (9.14 m) using a one-arm pull out from a push start. The distance the head surfaced from the wall and the time to 30 feet was recorded. Four weeks following the introduction and mandatory use of the double arm pull during training, identical testing procedures were repeated using the double arm pull. Results showed a time gain of 0.3 s over 30 feet and an increase in head surface distance of 1 foot 6 inches (0.46 m). Repeating the tests identically after three months saw further improvement in time of 0.462 s over 30 feet and head surface distance of 2’ 4” (0.71 m).

Beckett (1985) cited weaknesses in the methodology used by Adler (1979) as a reason for performing a similar study. To determine whether the one-arm or two-arm pull out was faster, Beckett (1985) examined the push-off and pull-out phases separately. Twenty-four male and twenty-four female subjects aged 13-18 years were chosen from competitive and non-competitive swimming backgrounds. The duration of training was four weeks and consisted of explanation, demonstration and practice sessions. During this period, subjects were instructed to use the two-arm method on all freestyle sets in training or class. The non-competitive swimmers were instructed to practise both the two-arm and one-arm pull out methods.

Testing was conducted over two days. Day one involved an all out one- and two-arm pull out from a stationary start (no push) followed by the resumption of normal stroking past the finish point. Day two testing timed the combined push off and pull out method. Three all out efforts at each trial were performed with a five-min rest between trials. All time measurements were taken with an Automatic Performance Analyser, Model 741, with an accuracy of one-thousandth of a second (Beckett, 1985). Results supported Adler’s (1979) claim that the two-arm pull out was superior to the one-arm pull out. Mean performance time was faster for subjects utilising the two-arm pull out in both the push and pull and the pull out only trials. Statistical significance ($p<0.05$) was, however, shown in the test examining the pull out phase only. Despite Beckett’s (1985) claims, the pull out only condition eliminates the influence of leg power, the glide and somersault speed. Hence, it is speculative, based on this result to generalise the benefit of a two-arm pullout. The acceleration gained by using a two-arm pull out from a stationary position may not have the same advantage when the body is already travelling at a high velocity from the push. This may explain the non-significant result shown in the push off and pull trials.

The investigations of Adler (1979) and Beckett (1985) were limited due to measurement and experimental design problems by today's standards. Despite their findings, the double arm pull out following the turn has not been adopted as a conventional turn technique or further explored. The incidence of subject shoulder pain and soreness reported by Adler (1979) and Beckett (1985), as a result of performing the double arm pull, is thought to have contributed to the disregard of this technique.

Increased activity in turn research combined with increased measurement accuracy has seen researchers favour the breakdown of turn time analysis into various movement phases (Chow et al., 1984; Takahashi and Sakata et al. 1983; Wakayoshi, Nomura, Takahashi, Mutoh & Miyashita, 1992). Takahashi and Sakata et al. (1983) determined five, separate freestyle turn phases: turn preparation, rotation, wall contact, glide and stroke preparation. They then contrasted turn performances by eight trained and 27 untrained swimmers over a 10 m distance (5 m in to 5 m out). Comparison of time for each phase indicated highly significant differences in four of the five phases between the trained and untrained swimmers. No significant difference was observed in wall contact phase times and is likely to be attributed to the large variations exhibited by the untrained swimmers.

Comparison of turn times between swimmers during competitions has also been investigated and reported in the literature (Arellano, Brown, Cappaert, & Nelson, 1994; Chow et al., 1984). Chow et al. (1984) recorded and examined the turning techniques employed by all finalists in 19 individual swimming events at the 1982 Brisbane Commonwealth Games. Turn performance was captured using two 16 mm motion-picture cameras and analysis consisted of seven performance measures. No arbitrary distances were selected to define a turn for the purpose of this study. Instead, the timing of the arm stroke was used to signify initiation and completion of the turning motion. Distance-in was defined as the horizontal distance from the vertex of the head and the pool wall, at the instant the swimmer's forward hand entered the water during the last stroke before initiating the turn. Time-in was recorded as the duration from the point of distance-in to first contact with the wall. Distance-out was defined as the horizontal distance from the vertex of the head and the pool wall, at the instant the swimmer completed the first stroke following the turn. Time-out was recorded as the time elapsed from the moment the swimmer first made contact with the wall to the point of distance-out. Average velocity-in, velocity-out and total turn time were subsequently derived from these measurements.

Chow et al. (1984) observed significant differences between male and female swimmers in most of the distance and velocity measures, with males exhibiting larger mean values than females in all instances. The generally taller males were thought to have recorded larger distances-in and -out on the basis of their physical size and subsequent pool position in relation to turn initiation and completion. Also, it was postulated that if the male swimmers possessed greater strength in the lower limbs, greater horizontal impulse could be generated during wall push-off and result in greater distance-out and velocity-out values. Therefore, known gender differences in body size (Mazza, Ackland, Bach, & Cosolito, 1994) and lower body power (Miyashita, Takahashi, Troup & Wakayoshi, 1992) between males and females appear likely to contribute to variation in turning performances, and warrant consideration in turning studies (Lyttle, 1999).

Analysis of the freestyle events demonstrated mean values for distance-in and average velocity-in tended to decrease as race distance increased, for both male and female events. This finding was suggested to result from an increase in approach velocity to the turn due to increased swimming velocities in the shorter events (Chow et al., 1984). It was also hypothesised that swimmers in the longer events may attempt to conserve energy by not executing their turns with maximal effort. In contrast, Hay et al. (1983) concluded that the opposing influences of approach velocity and vigour of turning effectively offset each other and distance-in does not vary significantly with race distance.

For the longer freestyle events (1500 m for males and 800 m for females), significant negative correlations were found to exist for average velocity-out with total event time and the order of finishing (Chow et al., 1984). That is, the greater the average velocity-out, the less the race time and the higher the placing. Not surprisingly (Thayer & Hay, 1984), the correlation between total turn time and event time for the men's freestyle events increased with an increase in race distance (Chow et al., 1984).

Thayer and Hay (1984) assessed the turn performances of male swimmers during competitions by using arbitrary distances to define turn performance. These set distances were based upon earlier work (Hay et al., 1983) that identified consistent turn start and completion distances, based on arm stroke timing, over all freestyle race distances. Total turn distance was set at 9.5 m for freestyle events and comprised distance-in and distance-out lengths of 3 and 6.5 m, respectively. Turn time was defined as the time from the swimmer's head reaching the distance-in mark to the head reaching the distance out mark. Freestyle swim results showed turn times increased systematically with increases in race distance and the percentage of total race time spent turning ranged from 20.5 % for the 50 yard (45.72 m) event through to 36.5 % for the 1000 (914.4 m) yard event.

Arellano et al. (1994) also demonstrated an increase in freestyle turn times with increased race distance, when using arbitrary distances to define turn performance. Their investigation examined the performances of elite male and female competitors in the 50, 100 and 200 m freestyle events at the 1992 Barcelona Olympic Games. Total turn distance was set at 15 m and comprised equal distance-in and distance-out lengths of 7.5 m. Turn time-in, time-out and total turn time increased with an increase in race distance from 100 to 200m, for both male and female swimmers. The percentage of total race time spent turning also increased from 14.42 % for males and 14.75 % for females in the 100 m event to 21.69 % and 22.02 % in the 200 m event, respectively.

The uses of different methods for defining turn performance (arm stroking versus fixed distances) and variations within these methods make comparison between the investigations described above somewhat difficult and inappropriate. Nonetheless, the findings of these investigations highlight the importance of turning and the effect that improved freestyle turn performance may have on total swim performance.

The kinetics of swim turn performance

While early studies in turn research consisted primarily of time-based assessment (Beckett, 1985; Chow et al., 1984; Fox et al., 1963; King & Irwin, 1957; Scharf & King, 1964; Ward, 1976), more recent investigations have incorporated wall kinetics by using force platforms to examine turn performance (Blanksby et al., 1998; Blanksby et al., 2004; Blanksby, Gathercole et al., 1996; Blanksby, Hodgkinson et al., 1996; Daniel et al., 2002; Gathercole, 1994; Hodgkinson, 1994; Hodgkinson & Blanksby, 1995; Lyttle et al., 1999; Lyttle & Mason, 1997; Nicol & Kruger, 1979; Takahashi, Yoshida et al., 1983). Measurement of wall kinetics during turning has enabled both comparison of turn techniques (Nicol & Kruger, 1979) and elucidation of critical aspects of optimal wall contact during turning (Blanksby et al., 1998; Blanksby et al., 2004; Blanksby, Gathercole et al., 1996; Lyttle et al., 1999). The current literature presents kinetic investigations into turns from all the competitive swimming strokes, and for different strokes, ranging from untrained to trained, age-level to elite swimmers.

Swim turns are currently categorised as one of two types. Namely, a pivot turn preceded by a double hand touch evidenced in breaststroke and butterfly, or a somersault (tumble) turn as seen in freestyle and backstroke (Lyttle, 1999). With respect to turn kinetics, Lyttle and Mason (1997) noted marked differences in the force profiles of butterfly and freestyle turns. In addition, Blanksby et al. (1998) reported mean wall (foot) contact time (0.39 s) during breaststroke turns to be lower than that found for freestyle tumble turns by age-group swimmers (0.58 s) (Gathercole, 1995). Due to the varied turn techniques and kinetics in breaststroke and butterfly relative to freestyle, kinetic studies investigating these turn types are beyond the scope of this thesis and therefore, will not be explored in this review.

The majority of studies investigating turn kinetics have focussed on freestyle (Blanksby, Gathercole et al., 1996; Blanksby, Hodgkinson et al., 1996; Lyttle et al., 1999; Lyttle & Mason, 1997; Nicol & Kruger, 1979; Takahashi & Yoshida et al., 1983), while only one study is known to have examined backstroke turn kinetics (Blanksby et al., 2004). A change to the backstroke rules by FINA resulted in the backstroke turn evolving to include a forward somersault from a prone position, not unlike the freestyle turn. In consideration of the scope of the present work, a variety of these kinetic turn investigations will be explored.

Kinetics during freestyle turns

The first study to measure wall push-off kinetics during swim turns was conducted by Nicol and Kruger (1979). They attempted to achieve greater accuracy when analysing freestyle turns by using a time measuring device and a waterproofed two-dimensional (2D) force platform. Five trained university level swimmers (four females and one male) performed three trials with each of the following techniques: push off with glide only; freestyle flip turn; open freestyle turn; and a flip turn with glide only. Mean velocity was calculated from time measurements between the 6 m and 3 m mark before reaching the wall. In and out times of the swimmer from the measured intervals from the wall were recorded along with the horizontal impulse during push off and the length of glide after push off.

Conversion of kinetic energy from forward movement, allowing the body to rotate, had no effect on maintaining velocity in and out of the tumble turn (Nicol & Kruger, 1979). Conversely, the need for the leading arm to touch the wall prior to rotation and push off decreased forward swimming velocity in the open turn. As a result, the time taken to perform the open turn was increased by the inability to incorporate little or no forward swimming velocity into the out going velocity of the turn. No significant differences between the impulses relative to the push off and flip turn were reported. Despite this, a 15% decrease in the length of glide following the flip turn was observed. Nicol and Kruger (1979) cited greater resistance just after push off, caused by incomplete body rotation after the flip turn, as the likely cause of this decreased glide length. Another explanation may be increased resistive hydrodynamic flow, caused by the swimmer's approach, travelling in the opposite direction to the push off. The conclusion made by Nicol and Kruger (1979), however, was that the flip turn is an advantageous turn technique compared to the open turn.

Takahashi, Yoshida et al. (1983) investigated the relationship between the force generated against the wall during a turning motion and the horizontal velocity of the swimmer after turning. Three highly trained and three recreational male swimmers of mean height 171.0 cm and weight 70.7 kg were asked to perform under two conditions; a maximal push and glide from the wall, and a flip (tumble) turn and glide from the wall that was preceded by a ten meter freestyle swim approach. Three trials for each condition were performed from which turn force on the wall, right knee joint angle and horizontal swim velocity (maximal push and glide trials only), were measured.

Takahashi, Yoshida et al. (1983) reported the highly trained swimmers spent less time in contact with the wall and produced greater propulsive impulses and peak forces than the recreational swimmers, during the tumble turn. Despite substantial differences in these force measures between the groups, secondary analysis of the raw data by Lyttle (1999) determined these differences to be statistically non-significant ($p>0.05$). Tumble turn trials containing greater impulse and peak forces were accompanied with decreased wall contact time (WCT) and greater maximum knee flexion. Wall exit velocity was not obtained from the tumble turn trials due to measurement constraints. Therefore, the relationships between wall contact measures and exit velocity were not determined.

The freestyle turn force profiles reported by Takahashi, Yoshida et al. (1983) differ from those reported in more recent research (Blanksby, Gathercole et al., 1996; Lyttle & Mason, 1997). Takahashi, Yoshida et al. (1983) showed a mean force-time curve representing total wall contact to comprise a large initial peak that almost immediately decreased to zero. This impact spike was followed by a 0.08 s period of zero force, which was then followed by a tri-modal pattern of peaks that approximated two-thirds of the initial impact peak force. Force variations in the main push-off phase (tri-modal; 0.3 s) were subjectively attributed to the complicated motion of the turn (Takahashi, Yoshida et al., 1983). Actions such as initial foot contact, sculling the hands, stretching the arms and rotating the trunk were postulated as contributing factors. The period of zero force observed by Takahashi, Yoshida et al. (1983) can only be attributed to a break in contact between the swimmer and the wall (force plate). The bi- or tri-modal force-time curves reported by Blanksby, Gathercole et al. (1996) and Lyttle & Mason (1997) indicate no break in wall contact. Different turning techniques exhibited by current swimmers are a likely explanation for the differences observed in force-time curves between these investigations.

Force-time curves from the maximal push and glide trials indicated that force increased in two increments (bi-modal) to a mean peak of 833 N at 0.07 s before cessation of foot contact (Takahashi, Yoshida et al., 1983). The trained swimmers demonstrated higher mean impulse, greater maximal knee flexion and higher exit velocity values than the recreational swimmers. In addition, a significant ($p<0.05$)

positive relationship between the initial velocity of the swimmer's waist and the impulse generated against the wall was shown when calculated for all swimmers (n=6). Peak force during push-off from the static start occurred at an included knee joint angle of approximately 120^o (60^o of knee flexion). Similar ranges of knee angle ($120 – 140^o$) have been reported to correspond with peak force during vertical jumping (Ae, 1982, as cited in Takahashi and Yoshida et al., 1983) and a comparable range of knee extension ($114 – 125^o$) found during maximal isokinetic contractions for dynamic peak torque (Thorstensson, Grimby & Karlsson, 1976). The knee angle corresponding with peak force during the tumble turn was not reported. In summary, the findings of Takahashi, Yoshida et al. (1983) suggest static start and tumble turn performance differences between trained (skilled) and untrained (less skilled) swimmers can be observed from wall kinetic and kinematic data. Further, greater impulse applied to the wall during static starts resulted in greater wall exit velocity. This relationship was considered likely to apply to tumble turns also (Takahashi, Yoshida et al., 1983).

Blanksby, Hodgkinson et al. (1996) employed the use of a 2D strain gauge force plate to measure the freestyle turn kinetics of 10 male and 9 female, national level freestyle swimmers. Data were collected during 50 m freestyle sprint performances in a short course pool via two underwater video cameras and wall mounted force platform. Each subject performed three swim trials from which peak perpendicular force, total impulse, wall contact time (WCT) and 50 m, 5 m and 2.5 m round trip times (RTTs) were recorded.

Significant gender differences observed in 11 of the 14 variables measured resulted in male and female performances being considered separately. Results revealed significant ($p<0.05$) negative correlations between peak forces and both 5 m and 2.5 m

RTTs by the female group ($r_{5m\ RTT} = -0.77$; $r_{2.5m\ RTT} = -0.84$). This relationship implies that higher peak force applied to the wall during freestyle turns contributes to faster turn times. Further, WCT was positively correlated ($p<0.05$) to the 5 m and 2.5 m RTTs ($r_{5m\ RTT} = 0.76$; $r_{2.5m\ RTT} = 0.81$), implying increased WCT resulted in slower turn performance. In contrast, no such relationships were evidenced between wall kinetics and RTTs for the male swimmers.

Blanksby, Hodgkinson et al. (1996) performed multiple stepwise regression analyses to determine the predictive capabilities of the measured variables to RTTs. Results showed increased peak force to be the sole variable included in the stepwise regression equation to predict 2.5 m RTT for females and the only kinetic variable in the equation to predict 5 m RTT. No kinetic variables were added to the predictability of either of the 50 m regression equations for the females. In contrast, impulse was the only kinetic variable entered in both equations that predict 50 m RTT for males, with no kinetic measures present in the 5 m and 2.5 m RTT prediction equations. Variations in turning kinetics between genders were not explained by the authors. However, Lyttle (1999) believes this result simply highlights the differences between elite male and female swimmers. Further, he added that the low subject to independent variable ratio present in this investigation strongly limits the application of these findings to elite swimmers in general. Tabachnick and Fidell (1989) recommend a minimum subject to independent variable ratio of 5:1 for conducting multiple regressions, with higher ratios needed for stepwise regression.

Wall kinetics during freestyle turns performed by age-group swimmers have also been examined. Blanksby, Gathercole et al. (1996) used a 2D underwater force plate and two submerged video cameras to investigate numerous kinetic and kinematic features from tumble turns performed by 17 male and 19 female (11 – 13 years) swimmers. Each subject completed 3 x 50 m maximum effort freestyle swims in a 25 m pool on a 3-min departure time. The wall kinetic features consisted peak perpendicular force, total impulse and WCT. A discriminant analysis revealed no significant differences ($p<0.05$) between the male and female performances for 5 m RTT. Hence, all subjects were pooled into one group with a sample size of 36. For the kinetic measures, Pearson product-moment correlation coefficients revealed a significant, positive relationship between the 5 m RTT and WCT. This finding implies that decreasing WCT results in decreased turn times. Furthermore, significant and negative correlations were shown for peak force and impulse with 5 m RTT. Therefore, increased peak force and impulse during wall contact resulted in decreased turn times.

Blanksby, Gathercole et al. (1996) conducted a stepwise multiple regression analysis procedure to determine the best possible predictors of the 5 m RTT. Significant independent variables were added to the model when a variable was deemed to add predictability to the regression equation at $p<0.05$. Results of the stepwise regression for 5 m RTT indicated that the best predictors in order of importance were: peak force; swim resumption distance; turn start distance; and height. These five variables were found to account for 55 % of the total variance in 5 m RTT ($r = 0.775$). Peak force was the best single predictor of 5 m RTT accounting for 33 % of the variance, suggesting that increased peak force applied to the turning surface contributes appreciably to improved turn performance. A poor subject to independent variable ratio in this investigation once again limits the stepwise regression results to the present population sample.

Despite similarities in freestyle and backstroke turning motions, Blanksby, Gathercole et al. (1996) recorded substantially higher peak perpendicular force (693.4 ± 228.1 vs. 228.8 ± 69.6 N) and impulse (177.2 ± 50.2 vs. 55.6 ± 12.4 Ns) during freestyle turns than those observed during backstroke turns (Blanksby et al., 2004), for age-group swimmers. Wall contact times, however, were shown to be similar (backstroke: 0.59 ± 0.16 s; freestyle: 0.58 ± 0.20 s) between the two strokes. Age-group swimmers are notorious for swim turn performance variation. Hence, poor judgement during the backstroke turns is a likely explanation for these differences in wall kinetics. Prematurely rolling to the front in the backstroke turn could potentially cause a slowing down and subsequent loss of momentum to generate force on the wall (Lyttle, 1999). A dearth of research investigating backstroke turns currently prevents verification of a similar pattern existing between freestyle and backstroke turns in elite swimmers.

Walker (1996) is believed to have conducted the first turn investigation using a 3D underwater force platform. Seventy-three age-group swimmers each had two freestyle turn performances recorded, from short course swims at race pace, using three above water and two underwater video cameras. Turn kinetics were obtained via an unspecified, wall mounted, 3D force platform. However, the reported findings were descriptive only and were based on trends associated with an average swimmer's turn. Nonetheless, Walker (1996) noted that faster turn performance was subjectively associated with increased impulse applied to the wall in the horizontal direction and minimising forces in the lateral and vertical directions. Greater than minimal lateral or vertical forces applied to the wall during push-off were hypothesised to result in a less than optimal direction of travel (straight line towards the other pool end) and therefore cause an increase in turning time (Walker, 1996). Despite the noted trends in findings, the lack of methodological description and statistical inference renders these findings anecdotal and of minimal use.

Lyttle and Mason (1997) examined the kinetic and kinematic parameters affecting freestyle turns performed by three elite male swimmers. Turn kinematics from the approach, push-off and glide phases were analysed using the Kinex Swimming Analysis System. A turning board instrumented with four Kistler tri-axial force transducers (3D), mounted on the pool wall, and was used to measure peak perpendicular force, total impulse and WCT from each performer over a minimum range of seven maximal swim trials. During their investigation, Lyttle and Mason (1997) developed a method for separating swimmer wall contact forces from a known bow wave force effect. Consequently, WCT was defined as the time from the beginning of an initial increase in vertical and horizontal forces and finished when a zero perpendicular force was reached.

Due to the small subject population (n=3), Lyttle and Mason (1997) limited their analysis to descriptive statistics of means and standard deviations. For reasons that were unexplained, vertical and horizontal (lateral) forces were not separately analysed or reported. Profiling of the perpendicular forces recorded during freestyle turning indicated a bi- or tri-modal force curve resulting from foot contact (peak force: 1345.3 ± 236.5 N; impulse: 247.3 ± 29.0 Ns), which lasted approximately 0.3 s. Average WCT during this investigation was demonstrated to be an average of 0.18 s shorter than those reported in pervious studies (Blanksby, Gathercole et al, 1996; Nicol and Kruger, 1979; Takahashi, Yoshida et al., 1983). This observed difference was mainly attributed to the separation of bow wave forces from swimmer contact force. From their findings, Lyttle and Mason (1997) hypothesised that there may be an optimal trade-off between the impulse achieved during wall push-off and the time spent on the wall, in order to achieve a faster wall exit velocity.

More recently, Lyttle et al. (1999) investigated selected freestyle turn kinetic, hydrodynamic and kinematic variables from turns performed by 30 experienced male swimmers. Wall kinetics consisting of peak perpendicular force, total impulse and push-off time were recorded via a vertically mounted 2D force plate. This study varied uniquely from those preceding it by measuring the time-spent pushing-off (active portion of wall contact), in addition to total WCT. The push-off time represented the period from first forward displacement of the hips after wall contact until the feet left the wall (Lyttle et al., 1999). Each swimmer's centre of gravity (CG) acceleration and wall exit velocity were calculated from underwater videography, while hydrodynamic peak drag force and drag impulse were calculated from the kinetic and kinematic data using a derivative of Newton's second law.

Lyttle et al. (1999) conducted a stepwise multiple regression analysis procedure to determine the optimal combination of kinetic and hydrodynamic variables that best predicted faster push-off velocity. The CG velocity of the swimmer was used as the criterion variable and significant independent variables were added to the model when a variable was deemed to add predictability to the regression equation at $p<0.05$. Results from this procedure indicated that the best predictors in order of inclusion were: push-off time, peak drag force; and peak propulsive force. These three variables were found to account for 64 % of the total variance in push-off velocity ($R = 0.80$). This finding and the relevant correlations suggest longer wall push-off time; smaller drag force and higher peak perpendicular force result in a higher final wall exit velocity for the swimmer. However, the relationships between these variables are considered critical, such that, their effect should be examined in combination rather than individually.

Beta weightings from the stepwise regression analysis revealed peak drag force as the most influential variable for predicting the swimmer's final push-off velocity. This further highlights the importance of drag in turning technique. The application of higher peak force (second highest beta weighting) is therefore, only likely to contribute to higher push-off velocities if drag force is not appreciably increased simultaneously (Lyttle et al., 1999). For example, the production of higher peak push-off force and the corresponding instantaneous velocity would cause the resulting drag force to be increased exponentially. Also, Lyttle et al. (1999) noted that the proportion of total WCT spent pushing-off might be a crucial factor in determining final push-off velocity. A high WCT could negatively affect overall turn velocity if a low percentage of time on the wall is spent pushing. Conversely, a low WCT incorporating a rapid push-off might not allow sufficient time to develop optimal impulse. Thus, an optimal combination of low peak drag force, high peak propulsive force and a wall push-off time of sufficient period to develop this force are required to achieve a high push-off velocity (Lyttle et al., 1999). Furthermore, the authors proposed that it might be advantageous to gradually develop push-off force after planting the feet on the wall. This strategy is thought to allow peak force to be achieved closer to leaving the wall, without the prior development of excessive drag.

Primarily, comparison of freestyle turn kinetics studies indicates the magnitude of peak propulsive force and impulse increase, and WCT decreases from age-group to recreational and then elite level swimmers, respectively (see Table 2.1). The substantially higher peak force and impulse reported by Takahashi, Yoshida et al. (1983)

for three highly trained swimmers are considered a likely result of the initial spike and tri-modal force application pattern observed in this investigation. As can be expected, adult swimmers (elite and recreational) demonstrate considerably larger peak force and impulse wall kinetics than age-group swimmers, due to increased body weight and greater lower body strength (Miyashita et al., 1992). In addition, the lower WCT for the elite swimmers indicated that these swimmers could develop high amounts of force in a shorter period of time. Notwithstanding the need to optimise WCT, Lyttle et al. (1999) suggest that higher proportions of WCT spent pushing off is also likely to result in faster push-off velocity and maximise the use of elastic energy and muscle pre-stretch mechanisms.

The sizeable standard deviations relative to mean scores observed for the age-group swimmers, for all kinetic measures, are indicative of larger variation in turn performance. This greater variation is attributed to lower skill levels, as experienced swimmers are more likely to have fine-tuned their turn performances. Nonetheless, large variation in turn performances by age-group swimmers make this population ideal for discriminating between and identifying critical features of good turn technique.

Table 2.1. Summary of the previous freestyle kinetic turn studies (Adapted from Lyttle et al., 1999).

Study	Subject Population	Peak Force (N)	WCT (s)	Impulse (Ns)
Blanksby, Gathercole et al. (1996)	36 competitive age-group swimmers (19 female, 17 male)	693.4 ± 228.1	0.58 ± 0.20	177.2 ± 50.2
Hodgkinson & Blanksby (1995)	10 National level males	1303.3 ± 228.5	0.38 ± 0.07	290.2 ± 48.1
Lyttle et al. (1999)	30 experienced adult males	* 1189.6 ± 246.0	0.32 ± 0.04	* 204.0 ± 54.9
Lyttle & Mason (1997)	3 International level males	1345.3 ± 236.5	0.29 ± 0.05	247.3 ± 29.0
Nicol & Kruger (1979)	5 University trained swimmers (4 female, 1 male)	----	0.51 ± 0.11	217.0 ± 28.0
Takahashi, Yoshida et al. (1983)	3 highly trained males	1711.7 ± 379.1	0.36 ± 0.06	301.8 ± 41.5
	3 recreational level males	1068.0 ± 191.4	0.48 ± 0.06	223.6 ± 6.14

Note: * Calculated only during the time of push-off.

In summary, the findings from freestyle turn studies across several levels of swimming proficiency indicate the presence of trends in kinetic parameters with respect to turn performance. Generally, development of higher peak propulsive force and impulse during wall contact (Blanksby, Gathercole et al., 1996; Blanksby, Hodgkinson et al., 1996; Takahashi and Yoshida et al., 1983), minimising vertical and lateral wall forces (Walker, 1996), in combination with lower WCT (Blanksby, Gathercole et al., 1996; Blanksby, Hodgkinson et al., 1996; Lyttle & Mason, 1997; Takahashi and Yoshida et al., 1983) produces faster freestyle turn times. Furthermore, the latest research indicates that higher push-off velocities from freestyle turns are achievable when combinations of low peak drag force; high peak propulsive force and an increased wall push-off time are optimised (Lyttle et al., 1999). That is, when turning, gradual development of wall force so that peak force occurs later in the push-off (when the swimmer is more streamlined) decreases the effect peak drag force has on wall exit velocity (Lyttle & Benjanuvatra, 2004). Finally, empirical data for 3D force profiles in freestyle turns, across all swimming proficiencies, are not reported.

Wave Forces during Turns

Kinetic analysis during turning has been made possible due to the development of waterproof force platforms. When mounted vertically at the end of a pool, wall contact forces produced by the swimmer can be profiled. However, early turn kinetic research (Blanksby et al., 1995; Nicol and Kruger, 1979; Takahashi, Yoshida et al., 1983) failed to consider that such force profiles not only incorporated the forces applied by the swimmer, but additional forces due to waves and turbulence created by the approaching swimmer. Failure to separate wave and turbulence forces from the swimmer's applied force would not allow measures such as the swimmer's impulse and time on the wall to be precisely quantified (Lyttle, 1999). The likelihood that these wave and turbulent forces masked the forces applied by the swimmer is therefore considered a major limitation to their reported findings.

Lyttle and Mason (1997) recognised the presence of a bow wave effect from force profiles in their kinetic analysis of freestyle and butterfly turns. Consequently, they developed an analysis technique in an attempt to separate the bow wave from swimmer contact forces. A manual trigger was activated during trials that subjectively coincided with swimmer wall contact. This trigger was found to coincide with sharp increases in lateral and vertical directional forces, from which wall contact was defined. Lyttle and Mason (1997) reported these hypothesised wave forces contributed up to 500 N of pre-contact force. However, the magnitude of this force is dependent on the size of the force plate used (Lyttle, 1999).

Further, but unsuccessful attempts to separate wave and turbulence forces from swimmer contact forces have also been made. Blanksby et al. (1998) used a signal processing approach and reported the bow wave frequency to be similar to that of the force generated by the swimmer. However, they concluded total elimination of the bow wave effect could not be obtained without a loss of swimmer wall contact force data. Roesler (2002) attempted to quantify the bow wave effect using two 500 x 500 x 180 mm underwater force platforms positioned vertically on the pool wall, as close together as possible. Five swimmers each performed nine turns on the lane centred force platform, while wall kinetics were recorded simultaneously on both platforms. Despite only brief methodological discussion and no statistical details described, Roesler (2002) reported an observed bow wave force of nearly one tenth of the maximum registered force occurring in all measurements. The second platform also indicated a wave force effect of smaller magnitude due to its position in relation to the turning swimmer.

The most recent attempt to quantify the bow wave effect was performed by Blanksby et al. (2004). They explored several methods of quantifying the bow wave force effect using pressure transducers attached to the force plate. Despite this approach, their efforts were unable to accurately measure wave force due to changes in static pressure caused by varying wave heights. Investigations using metal grids attached to the front of the force plate indicated grids with smaller holes resulted in lower wave force being transmitted through to the force plate. From this method it was estimated that the bow wave force represented approximately 10 % of the kinetic profile, although this is dependent on the size of the force plate used (Blanksby et al., 2004).

Clearly, past and future investigation into the kinetics of turning is not without limitation due to the inability to separate bow wave and turbulence forces from swimmer wall contact forces. Without further technological developments or equipment modifications, the present options available to the researcher in relation to turn kinetic analysis are to either ignore the bow wave effect (Blanksby et al., 1998) or subjectively attempt to eliminate it (Lyttle & Mason, 1997).

The kinematics of swim turn performance

As for swim turn kinetics, the current literature presents investigations of selected turn kinematics for each of the competitive swimming strokes (Blanksby et al., 2004; Blanksby, Gathercole et al., 1996; Blanksby, Hodgkinson et al., 1996; Huellhorst, Ungerechts & Willimczik, 1988; Lyttle et al., 1999; Lyttle & Mason, 1997; Takahashi, Yoshida et al., 1983). Due to the use of different turning strategies to that of a tumble turning motion, kinematic turning studies for breaststroke and butterfly have not been implicitly explored and are referred to only where findings are deemed applicable to freestyle turn performance.

Kinematics during freestyle turns

Early freestyle turn research consisted primarily of time-based measures (Adler, 1979; Fox et al., 1963; King & Irwin, 1957; Scharf & King, 1964; Ward; 1976). More recent technological advancements have allowed a variety of kinematic measures to be examined and with greater accuracy. Therefore, this section of freestyle turn kinematics will focus primarily on those alternate kinematic measures, not previously discussed in this review. While many recent kinematic investigations incorporate turn kinetics also, further reference to the kinetic aspects of these investigations are not made unless deemed appropriate.

In addition to the timing and distance measures employed by early turn research, more recent turn investigations have explored additional kinematic parameters such as: joint angles (Takahashi, Yoshida et al., 1983); body segment lengths (Blanksby, Gathercole et al., 1996; Blanksby, Hodgkinson et al., 1996); depth displacement information (Mason & Pilcher, 2002); and velocity characteristics of wall push-off (Blanksby, Gathercole et al., 1996; Blanksby, Hodgkinson et al., 1996; Huellhorst et al., 1988). Takahashi, Yoshida et al. (1983) attached an electrogoniometer to each subject's right knee to measure knee joint angle changes (angle between the shank and thigh) during wall push-off. During freestyle tumble turn trials, the three highly trained swimmers recorded mean maximal knee flexion (means ± SD) of $76.33^{o} \pm 24.98^{o}$ compared with $42.33^{o} \pm 8.33^{o}$ demonstrated by the recreational swimmers. A similar trend in maximal knee flexion was observed during the push-off only trials (highly trained: $55.66^{o} \pm 12.86^{o}$; recreational: $49.00^{o} \pm 8.00^{o}$). The higher peak forces and impulse recorded for the trained swimmers indicates greater wall push-off forces were generated from shallower knee angles. Peak wall force was reported to occur at an included knee joint angle of approximately 120^{o} (60^{o} of knee flexion) (n = 6).

The superior turn performances and shallower knee flexion angles demonstrated by the trained swimmers indicates that wall contact with straighter legs may be beneficial. Blanksby, Gathercole et al. (1996) explored this theory by examining, among other variables, the degree of maximum tuck during wall contact from tumble turns performed by 17 male and 19 female age-group swimmers. The degree of maximum tuck was defined as the point when the hip was at its minimum distance from the wall during foot contact and was expressed as a percentage of the trochanteric height (tuck index). Results from a Pearson correlation coefficient matrix indicated significant ($p<0.05$) negative correlations between the tuck index and 50 m time, 5 m RTT and 2.5 RTT (Blanksby, Gathercole et al., 1996). This finding indicates that that the larger the tuck index (straighter legs), the faster the time will be. However, Blanksby, Gathercole et al. (1996) noted that the association between tuck index and trip times is stronger as the RTT decreases due to the turning component representing a higher fraction of the time. The authors hypothesised that a higher tuck index results in the swimmer travelling less distance during each turn and therefore, covering the trip distances faster. Despite the significant correlations between tuck index and RTTs, tuck index did not feature in a multiple stepwise regression as a predictor of the 5 m RTT (Blanksby, Gathercole et al., 1996). It is likely an optimal tuck index exists as close to full extension of the legs will not provide sufficient force generation from the push-off.

Blanksby, Hodgkinson et al. (1996) examined tuck index during their investigation of freestyle turns by nine elite female and ten elite male swimmers. For males, a higher tuck index was related to decreased 5 m RTT and significantly ($p<0.05$)

related to decreased 2.5 m RTT. Multiple stepwise regression analyses showed tuck index, which recorded significant relationships with greater distance in and peak force, to be the sole best predictor of 2.5 m RTT for men (Blanksby, Hodgkinson et al., 1996). Blanksby et al. (2004) also demonstrated higher tuck indexes produced greater peak propulsive forces during backstroke turns by age-group swimmers. Despite lacking significance, Blanksby, Hodgkinson et al. (1996) also reported negative relationships between tuck index and trip times, for the females. Therefore, it appears that an increased tuck index (straighter legs) can result in a swimmer covering less distance-in and out from the turn. Provided sufficient force can be generated with the legs in a straighter position, turn times can be reduced.

Mason and Pilcher (2002) examined whether the maximum depth and the corresponding distance from the wall were important characteristics of start and turn performance at the Sydney 2000 Olympics. All freestyle event semi-finals and finals were analysed using two underwater video cameras. Pearson product-moment correlation coefficients indicated no relationships existed for maximum depth and distance with total turn time. Therefore, the assumption that better turn performers have a tendency to spend more time and greater distances underwater would also result in greater maximum depth was unsubstantiated by these findings.

While it is clear that several kinematic parameters play critical roles in turn performance, comprehensive assessment of turn kinematics is lacking. Hence, further turn kinematic investigations are required to conclusively quantify critical elements of freestyle turn performance.

Reliability of turn performance and measurement

Only one investigation has been performed to specifically explore the reliability of swim turn performance and kinetic measurement. Blanksby, Gathercole and Marshall (1995) examined the reliability of an underwater 2D strain gauge force plate via repeated freestyle tumble turns. One elite male swimmer performed 10 x 50 m maximal freestyle swims (short course) on two separate days to determine the intra-individual reliability of the kinetic data. The peak perpendicular force, total impulse and wall contact time were measured. The deviation from the mean for the 10 trials, when expressed as a percentage for peak force (day 1 - 24.4%; day 2 - 20.4%), WCT (day 1 - 18.5%; day 2 - 17.6%) and impulse (day 1 - 17.6%; day 2 - 11.8%) did not show significant variation across the 10 trials on both occasions (Blanksby et al., 1995).

The reliability of swim turn performance was assessed using three elite male swimmers who each performed the same 10 x 50 m protocol on two separate days. During these trials, only 50 m, 5 m and 2.5 m RTTs were recorded. A Spearman Browne split-halves method of analysis indicated no significant difference existed between the 10 trials (Blanksby et al., 1995). Also, mean 5 m RTT for swimmer 1 was the only measure to vary by more than 5 % across the two test days. The findings of Blanksby et al. (1995) support the common biomechanical practice that three trials are sufficient to provide realistic data, representative of normal performance. Therefore, reliable turn performance kinetics can be observed in elite swimmers from as few as three trials.

The reliability of turn performance in age-group swimmers is not known. However, the usually large variability demonstrated in age-group performance indicates that poor reliability would be observed. Nonetheless, performance variation is often desirable when attempting to discriminate between the relative importances's of selected performance variables. Hence, selecting the best trial from a series of trials would also appear an appropriate method for turn performance analysis within this population.

Hydrodynamics and freestyle tumble turn performance

During turning, a swimmer aims to change direction with a minimal loss of speed and time. Optimising propulsion during wall approach, contact, and exit have been clearly demonstrated to improve turn performance. In addition to optimising propulsion, minimising the resistance to motion experienced by the swimmer due to travelling through water is highly beneficial. This resistance to motion is known as hydrodynamic drag. By minimising the hydrodynamic drag experienced by a swimmer, forward velocity from propulsive forces can be maximised. Hay (1992) stated that drag is a major determinant of swim turn performance and that optimising the balance between propulsion and drag is necessary for improved turn performance.

Total drag

The total drag experienced by a swimmer results from a complex combination of factors. The relationship between these factors can be expressed mathematically as:

$$F_D = (\rho v^2 AC_D) / 2$$

Where F_D is the total drag force, ρ is the density of the water, v is the velocity of the swimmer relative to the flow, A is the cross-sectional area of the swimmer in the direction of travel, and C_D is the coefficient of drag, which is an empirical constant (Cappaert & Gordon, 1998).

The coefficient of drag (C_D) is a function of the water flow characteristics determined by the object's shape and attitude and is therefore considered an indicator of good or poor technique (Cappaert and Gordon, 1998). The C_D depends on the shape of the body, the roughness of the surface and the state of the flow of the fluid (Ungerechts, 1983b). Whether laminar or turbulent, the flow of fluid is difficult to measure and is therefore estimated on the basis of the Reynolds number (Re). Ungerechts (1983b) describes the non-dimensional Re as a mathematical representation of the ratio of inertial to viscous forces on rigid bodies and characterises the state of flow as laminar or turbulent.

The mathematical equation for the Reynolds number is expressed as:

$$Re = vl / \nu$$

Where v = swimming velocity, l = length of the body and ν = viscosity of the water.

Numerous experiments with rigid bodies of different shapes over a wide range of Re values have shown that the C_D is a function of Re (Ungerechts, 1983b). Clarys (1979) determined the dependence of C_D from Re. Experiments with swimmers towed in rigid form demonstrated the flow of fluid around a rigid human body to be totally turbulent with total drag remaining high.

Types of drag

Karpovich (1933) derived three separate drag components likely to be experienced by swimmers from the plane and ship building literature documented by Froude in 1874 and Lanchester in 1908. These components were; skin friction, eddy resistance and wave making resistance. These components are now commonly recognised as frictional, form and wave drag (Rushall, Holt, Sprigings & Cappaert, 1994). Larsen, Yancher and Baer (1981) stated that for free surface penetrating bodies such as ships, wave and form drag have been estimated to comprise between 80 and 82 % of total drag resistance. While frictional drag is estimated to represent between 18 and 20 % of total drag resistance. It is considered that traditional fluid dynamic theory may not apply to human swimming given the non-streamlined nature of the human body (Clarys, 1979; Gadd, 1963). Furthermore, Clarys (1979) reported significantly higher drag values for self-propelling bodies than for those recorded when passively towed. As a consequence, the relative contributions of the frictional, form and wave drag components to total drag force for humans are rather complex and have not been demonstrated (Lyttle, 1999).

If freestyle turns are to be explored with the aim of enhancing performance, a thorough understanding of the frictional, form and wave drag components acting on a swimmer is required. These components will now be explored, firstly in general fluid dynamic terms, then in further detail with relation to both active and passive human swimming.

Frictional drag

When two surfaces slide, or attempt to slide over one another, the force limiting their motion is known as friction (Hay, 1992). In swimming, the component of friction recorded when water passes over the surface of the body and limits their motion relative to each other is known as frictional drag. The mechanism behind this phenomenon relates to the viscosity characteristics and the flow of the fluid (Clarys, 1979), and the nature of the skin surface (Rushall et al., 1994). That is, frictional drag occurs and retards a swimmer's motion as a result of turbulent flow caused by the contact of the fluid with the skin. The water particles in direct contact with the skin (boundary layer) swirl violently in a tangle of microscopic eddy's (Rushall et al., 1994) and are reduced to a relative velocity of zero (Clarys, 1979). This velocity gradation between the boundary layer and the still water exerts a tangential shearing pressure on each surface of the swimmers body and gives rise to the frictional drag resistance (Clarys, 1979). Rushall et al. (1994) claim the secret to minimising frictional drag is to maintain laminar flow, a condition where the fluid passes smoothly over the skin surface allowing the body to slide through the water.

A major factor affecting the magnitude of frictional resistance is surface smoothness. Surface irregularities and natural roughness are enough to spoil laminar flow and cause turbulent flow. Improved knowledge and increased emphasis placed on reducing frictional drag by scientists, coaches and swimmers have spawned several innovations in swimming performance. The wearing of latex caps provide a smoother surface than a head of hair, as do tighter swim suits made of sheer fabric with minimal seams and edges. Rushall et al. (1994) indicate these adaptations are recognised ways that reductions in frictional drag can be achieved. van Manen and Rijken (1975) demonstrated that a typical female swimming suit worn in the 1970's added approximately 9 % to the total body drag estimated from towing trials with and without the suit worn. The removal of body hair has been shown to decrease the physiological cost of swimming at maximal velocity compared to an unshaven condition (Sharp & Costill, 1990; Sharp, Hackney, Cain & Ness, 1988) and significantly reduce the rate of velocity decay during a prone glide following a maximal underwater push-off (Sharp & Costill, 1989).

While minimising the production of turbulent boundary layer flow against the skin is ideal for reducing frictional drag, a perfectly smooth surface is not considered optimal. According to Rushall et al. (1994), a surface with a fine texture is able to hold a thin film of water that is then carried along as part of the swimmer. This results in a less turbulent boundary layer as friction between layers of water on water is considerably less than very smooth skin and water (Imhoff & Pranger, 1975; as cited in Rushall et al., 1994). Recent advancements in technology have enabled swimming suit design to exploit this phenomenon. Benjanuvatra, Dawson, Blanksby and Elliott (2002) found swimmers wearing full-length Fastskin™ swimsuits produced passive drag values that were significantly less than normal swimsuits, during towing at velocities between 1.6 and 2.8 $m.s^{-1}$.

The magnitude of the frictional drag that a given body experiences is reported to be dependent on the velocity of the flow relative to that of the body, and the total body surface area (Hay, 1992). The relationship between a swimmer's velocity and the frictional drag incurred is reported to vary from linear (Sheehan & Laughrin, 1992; Rushall et al., 1994) to a power of 1.7 – 1.92 (Karpovich, 1933). A linear relationship implies a relatively minor effect on performance as velocity increases. However, frictional (surface) drag is only active when the surface causes turbulent flow as the fluid follows the object form. Once the flow of fluid separates from the body, surface drag is minimised. Poor hydrodynamic shape due to numerous asperities and angular changes on the human surface cause many pockets of fluid separation to occur. This abundance of turbulent pockets covering a swimmer's surface therefore negates the formation of frictional drag. Thus, only those portions of the body surface that entertain frictional flow are responsible for frictional surface drag and not the total body surface area. Therefore, if a swimmer's total surface area were included in calculations of resistance, inferential errors would result. Despite the low contribution of frictional resistance to total drag resistance, consideration and minimisation of frictional drag has been demonstrated to enhance swim performance and is likely to also apply to turning motions.

Form drag

As the name implies, form drag is the component of drag resistance that relates to the ‘form’ a body adopts while moving through a fluid (Costill et al., 1992). The mechanism behind this phenomenon relates to the shape (cross-sectional area) of the body and to a lesser extent, the density of the water (Rushall et al., 1994). When a swimmer moves through water, the fluid layers are deflected around the body of the swimmer. The boundary layers of fluid follow the contour of the body until the flow is either greatly slowed due to a pressure increase or accelerated due to a pressure decrease. At this event, turbulent (eddy) flow is generated and the boundary layers of flow separate from the body (Farell, 1971). Differences in water pressure between the turbulent areas associated with boundary layer separation and the non-turbulent flow area immediately preceding the swimmer result in generation of a pressure gradient. This pressure gradient causes a resistive force to act perpendicular to the body’s frontal surface area, subsequently retarding the forward motion of the swimmer (Rushall et al., 1994).

The velocity at which the swimmer is travelling and the body cross-sectional area presented to the on-coming flow governs the magnitude of resistive form drag. Form drag is known to increase by the square of the velocity (Karpovich, 1933; Rushall et al., 1994; Sheehan & Laughrin, 1992). However, any attempt to reduce a swimmer's form drag by decreasing velocity is considered counter productive to the aim of increasing forward velocity. Unlike uniformly shaped objects, turbulence and pressure gradients are generated behind and around a number of body parts during swimming (Lyttle, 1999). This is particularly so for regions where the body suddenly changes shape such as the head, shoulders, elbows, hips, knees and feet (Clarys, 1979). Therefore, to reduce form drag a swimmer should maintain their body position with minimal inclination (Costill et al., 1992; Maglischo, 1993) and accentuate streamlining at every opportunity (Rushall et al., 1994). Streamlining is a process where the disturbance an object causes to the flow of a fluid is minimised (Bartlett, 1997). In swimming, good streamlining involves minimising excessive vertical and lateral movements to therefore decrease the cross-sectional area exposed to the on-coming flow of fluid. Kolmogorov and Duplischeva (1992) demonstrated that swimmers of similar body size (height and mass) could have drastically different active drag values. Similarly, Clarys, Jiskoot and Lewillie (1973) found body inclination to increase the frontal surface area of the swimmer and contribute to increased drag during passive towing studies. These findings suggest that good streamlining and body positioning can significantly increase swimming velocity by decreasing resistance.

Rushall et al. (1994) articulate that if a swimmer's action or body position creates an increased cross-sectional area then progress through the water will be retarded. This concept applies equally to body position during the wall push-off and glide from a turn. Therefore, any attempt to modify turning technique should accommodate streamlining for performance optimisation.

Wave drag

Wave drag is the component of drag resistance that results from a swimmer creating waves, wakes and turbulence (Rushall et al., 1994). The mechanism behind this form of resistance is a loss (transfer) of energy from the propulsive work of the swimmer to the creation of wave systems (Barthels, 1977; Rushall et al., 1994). Any accentuated vertical and lateral body movements during swimming cause pressure differences in and the displacement of fluid into waves. These, waves consist of masses of water lifted up against the force of gravity (Videler, 1993) and result in disturbances to the water's surface (Clarys, 1979). The wave drag results predominantly from turbulence at the air-water interface (Costill et al, 1992; Maglischo, 1993) and has been shown to become progressively less important with increasing depths (Hertel, 1966; Lyttle, Blanksby, Elliott & Lloyd, 1998)

Wave drag depends on, among other things, the swimmer's velocity, body shape and movements in proximity to the water surface (Hay, 1992). Wave-making resistance was first thought to vary as the fourth power of velocity (Peabody, 1917; as cited in Karpovich, 1933). On the basis of more recent investigations, wave drag is now considered to increase with the cube of velocity (Sheehan & Laughrin, 1992; Maglischo, 1993; Rushall et al., 1994). Hence, wave drag is considered the worst form of drag because its contribution to resistance increases dramatically with increased swimmer velocity (Rushall et al., 1994).

Pioneering work into ship design by Froude (1874) and his contemporaries demonstrated that, among other things, the length of an object was related to wave drag. They originated a dimensionless number, known as the Froude number, as the ratio between the inertial forces due to flow interference and gravitational forces (Larsen et al., 1981). The equation for the Froude number is expressed mathematically as

$$F_l = v / \sqrt{gl}$$

Where F_l is the Froude number, v is the velocity of the object, g is the gravitational constant, and l is the length of the object.

Wave drag is often expressed as a function of the Froude number (Bartlett, 1997) and application of this principle forms the basis of modern ship design (Larsen et al., 1981). In swimmers, the maximum Froude number that a swimmer can achieve is reported to be between approximately 0.42 (Larson et al., 1981) and 0.45 (Videler, 1993). Maximal Froude numbers in this range are limiting in that the required stroking power of a swimmer increases to the fifth or six power of the velocity (Larsen et al., 1981). Hence, large increases in stroke length or power will only result in small increases in velocity, as a consequence of increased wave drag (Larson et al., 1981; Videler, 1993).

The relationship between a body's Froude number and wave drag indicates that taller swimmers will produce less wave drag. According to Larsen et al. (1981), this implies that fast young swimmers achieve higher swimming velocities primarily by growing longer. Maintaining a stretched body position during swimming enables the swimmer to achieve greater average length and therefore decrease their instantaneous Froude number and wave drag, respectively (Larsen et al., 1981). Elimination of unnecessary vertical and lateral movements is also considered essential for minimising resistive forces due to wave drag (Rushall et al., 1994). Hence, movements such as ‘smashing’ the arms into the water from the recovery (Costill et al, 1992), lateral leg sway caused by a lateral arm recovery (Maglischo, 1993), excessive lifting of the head when breathing in freestyle (Rushall et al., 1994) and pushing off the wall at the air-water interface (Lyttle, 1999) should be minimised.

It is well established that amphibian movement in proximity to the air / water interface creates surface waves and that the energy required for their creation increases the energy costs for propulsion (Hertel, 1966; Prange & Schmidt-Nielson, 1970; Williams & Kooyman, 1985). Attempts to quantify the relationship between depth of movement and energy loss due to wave drag were pioneered by Hertel (1966). He investigated the coefficient of drag experienced by a spindle shaped object, with a relative thickness of 18 %, when towed at varying depths of immersion. The absence of wave drag was observed when the immersion depth of the axis of the spindle was approximately equal to three times the diameter of the spindle (see Figure 2.2). Maximum wave drag was observed when the object was located directly under the water surface, at an immersion depth equal to approximately 0.5 times the diameter of the spindle. Comparison of minimum and maximum drag force values indicated a fivefold increase in total drag force (Blake, 1983; Hertel, 1966).

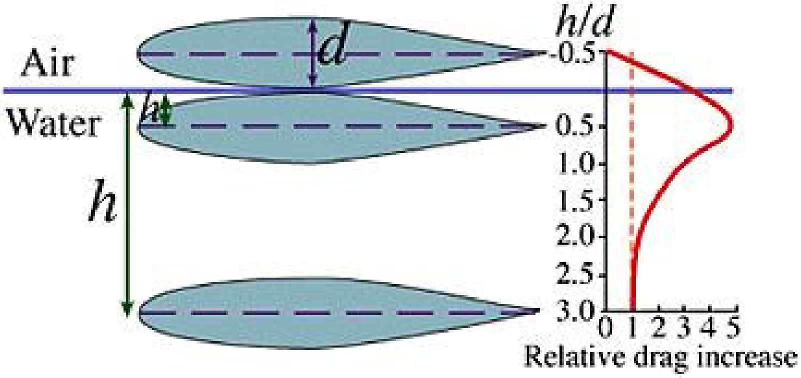

Figure 2.2 Drag on a streamlined body (largest diameter, d) as a function of the submerged depth (h) (adapted from Hertel, 1966).

Webb, Sims and Schultz (1991) demonstrated a significant positive relationship between water depth and distance travelled from fast-start performances of rainbow trout. They postulated that approximately 70 % of the mechanical work used to propel a fish in deep water is dispersed as waves when the dorsal (upper) surface of the trout is just out of the water. Their calculations indicated that energy dispersion of waves was reduced to zero at relative depths in excess of 3 times the maximal depth (vertical height) of the fish. Therefore, wave drag appears to be maximised when an object is immersed directly beneath the water surface (Hertel, 1966; Webb et al., 1991).

Larsen et al. (1981) applied fundamental fluid mechanics knowledge, obtained from boat design research, to swimming performance and determined the following. The contribution of wave drag to total drag becomes negligible at a depth equivalent to a depth-to-length ratio of 0.2 to 0.4. Gliding at depths of greater than approximately 0.2 of the swimmer’s length, in order to reduce wave drag during glide phases in swimming, are therefore suggested (Larsen et al., 1981). Lyttle (1999) calculated that a swimmer with a reach height of 2.5 m, travelling at a depth of 0.5 m underwater would fall within this range.

The literature presents conflicting findings for the resistive force (drag) experienced by swimmers when towed at various depths and velocities. Lyttle et al., (1998) reported significantly higher drag at the surface than 0.2, 0.4 and 0.6 m underwater. Furthermore, the drag at 0.2 m deep was significantly higher than 0.4 and 0.6 m depths for towing velocities between 2.2 and 3.1 $m.s^{-1}$. For the 0.4 and 0.6 m depths, however, no significant differences were revealed. In contrast, Jiskoot and Clarys (1975) found significantly higher drag forces 0.6 m underwater than at the surface. Given that wave drag increases with the cube of swimming velocity, the low glide velocities (1.5 – 1.9 $m.s^{-1}$) used by Jiskoot and Clarys (1975) may not have been fast enough to produce a substantial wave drag.

Larsen et al. (1981) also indicated that the depth of the water limits the maximum velocity a body could travel in a fluid, due to a fixed surface effect (the bottom). The equation for calculating the velocity maximum a body can reach with respect to the water depth is expressed mathematically as

$$V_{max} = \sqrt{gH}$$

Where V_{max} is the maximum velocity, g is the acceleration of gravity, and H is the water depth from the surface to the bottom.

Therefore, the limiting velocity a swimmer can travel at a pool depth of 1 m is slightly above 3 $m.s^{-1}$, and at a pool depth of 2 m, this limiting velocity increases to approximately 4.5 $m.s^{-1}$ (Lyttle, 1999). Larsen et al. (1981) claim that gliding velocities after starts and turns are 50 to 60 % higher than swimming velocities and are therefore limited by swimming pool depth. They postulate that for swimming times to be minimised, pool depths should be between 15 and 20 feet (4.57 and 6.09 m) deep. This phenomenon has implications for gliding and kicking following starts and turns whereby strategy and technique modifications that position the swimmer closer to the pool bottom may in fact increase drag. Consequently, technique modification to optimise start and turn wall exit techniques must accommodate this effect.

Despite unquestionable evidence indicating that drag limits a swimmer's motion, there are instances where drag may be beneficial to the swimmer. Swimsuit maker SPEEDO® claims to have incorporated 'gripper' fabric in the arms of their latest suit, the Fastskin™. The gripper fabric is claimed to increase sensory feel and grip on the water. This effect of increasing arm surface friction on swimmer performance is presently anecdotal and unsubstantiated by independent research. Form drag also contributes to hydrodynamic lift, particularly when accentuated on the hands and arms, and is essential in some strokes (Rushall et al., 1994). Further, Mason, Tong and Richards (1992) identified an intra-stroke period of centre of gravity acceleration unrelated to any obvious propulsive action of the swimmer, during butterfly swimming. They concluded that as a swimmer decelerates after the completion of the arm pull a wave of water generated by the swimmer surges forward and is used as a source of propulsion.

The contribution of friction, form and wave drag to total drag resistance in swimming is dependent on swim velocity (Toussaint, 2002). The reported exponential relationships between drag and velocity suggest that a doubling of swimming velocity would result in twice as much frictional drag, four times as much form drag, and an eight-fold increase in wave drag (Rushall et al., 1994). Toussaint (2002) suggests that at a constant velocity of 1 $m.s^{-1}$ the relative contributions to total drag will be: frictional drag ≈ 3 %, form drag ≈ 95 % and wave drag ≈ 2%. These contributions to total drag are reported to change to ≈ 3 %, 77 % and 20 %, respectively at a velocity of 2 $m.s^{-1}$. Wave drag and form drag are also believed to be inter-related, as increases in wave drag are also accompanied by increases in form drag, making their effects particularly noticeable (Rushall et al., 1994). Frictional drag is considered independent from wave and form drag (Larsen et al., 1981; Videler, 1993). However, these relationships are calculated primarily from traditional fluid mechanics theory developed from shipbuilding. Determination of the relationships between these drags and the human form are yet to be clearly established.

The contribution of added water mass to drag

A final consideration to the factors that contribute to drag resistance experienced by swimmers is the resistive effect produced by the acceleration of water mass. Theoretical fluid dynamics shows there is an acceleration dependent resistance known as the added mass concept. The mechanism behind this concept relates to acceleration of masses of water that remains in contact with the body segments that are causing propulsion and subsequently lead to an increase in the energy cost (Colman, Persyn & Ungerechts, 1998; Klauck, 1998).

The majority of research investigating resistance in swimming has been conducted using constant velocities and extrapolated over a wider range. Studies using this quasi-static approach have examined lift and drag coefficients for the hand, or arm and hand (Berger, de Groot & Hollander, 1995; Berger, Hollander & de Groot, 1993; Remmonds & Bartlett, 1981; Sanders, 1996; Schleihauf, 1979; Wood, 1979). The findings from these investigations, combined with underwater film analysis of the arm stroke, have enabled calculation of the hand and arm propulsive forces present during swimming (Payton & Bartlett, 1995; Schleihauf, 1979; Schleihauf, Gray & De Rose, 1983). However, measurement of propulsive and resistive forces in swimming using these methodologies only provides information about the velocity dependent resistance. Resistance due to acceleration and deceleration of the swimmer are therefore considered equivalent or have been neglected (Klauck, 1998; Ungerechts, 1983b).

Pai and Hay (1988) found that, for a cylinder oscillating about a transverse axis normal to the flow of fluid, 'added mass' and 'vortex shedding' effects contributed substantially to the force. However, these effects were shown to be considerably smaller at lower frequencies of oscillation in which the accelerations are smaller. Sanders (1996) attempted to develop a model for estimating forces produced by a swimmer's hand by extending the Schleihauf (1979) model to include coefficients that accounted for the effect of acceleration in the direction of flow. Applying these coefficients to data obtained from three-dimensional video analysis of a swimmer's hand indicated that forces contributed by the effective masses contributed up to 35 % of the total forces during the periods of greatest acceleration. Sanders (1996) concluded that the effect of accelerations of a swimmer's hand should be considered when seeking accurate estimates of the forces in swimming. Similarly, Bixler and Schloder (1996) demonstrated using computational fluid dynamics that hand acceleration may increase the propulsive drag force by as much as 40 % from that calculated using a quasi-static approach.

Klauck (1998) demonstrated the added water mass to range between 30 – 70 kg from measurement of swimmers during time dependent acceleration towing trials. Velocity and acceleration dependent components of the water resistance were derived from time dependent velocity curves, allowing estimation of the added mass for each swimmer. No explanation for the substantial variation shown in the magnitude of the added water mass between individual swimmers was given. The present author postulates that variations in swimmer size (frontal area and body length) and body position during towing are likely to have contributed to the variation shown in added water masses.

More recently, Coleman et al. (1998) investigated the effect of added water mass on a single swimmer's global centre of mass (mass of swimmer and added water mass) while performing an underwater dolphin kick. Differences in the acceleration and deceleration patterns for the added mass compared with the swimmer's centre of mass were observed. Less variation in the intra-cycle velocity for the global centre of mass was thought to account for these differences (Coleman et al., 1998).

The use of fluid mechanics has allowed greater insight into areas of swimming performance that traditionally have hampered a clearer understanding (Lyttle, 1999). Continued application of fluid mechanics principles and investigation into the forces experienced during swimming performance is likely to yield advancement in technique and performance. Turning motions in swimming require the swimmer to change direction and accelerate from the wall using a push-off. Therefore, the acceleration of the added mass is likely to contribute to resistive forces experienced during and after wall push-off following a turn.

When considering resistances that result from swimming actions, it is prudent to consider all forms of drag and whether any have been affected. Due to the increasing importance of drag as velocity increases, the high velocities experienced by a swimmer following the turn indicates that minimising drag resistance during turning motions is paramount. If turn technique changes are to be attempted, the effect on resistive drag has to be considered in order to enable a performance improvement. Any attempt to move faster through the water by producing more effort, and that effort results in greater amounts of unproductive movements, desired potential velocity benefits are likely to be offset by increases in added resistance (Rushall et al., 1994). With respect to drag reduction in swimming, Rushall et al. (1994) suggest that reductions in wave drag are of the highest importance, followed by form drag, then frictional drag.

Passive and active drag

Several authors highlight the importance of the glide, underwater kicking and stroke resumption phases following wall push-off from a turning motion (Blanksby, Gathercole et al., 1996; Lyttle & Benjanuvatra, 2004; Lyttle & Mason, 1997; Sanders & Byatt-Smith, 2003). The drag associated with each of these phases can be classified as either passive or active. Passive drag results when a rigid body moves through water such as the streamlined glide following wall push-off in the turn. Alternatively, active drag results from movements produced by the swimmer, usually when attempting to increase propulsion from kicking or stroking (Lyttle, 1999). Despite a lack of empirical knowledge regarding the relationships between the components of drag and swimming velocity, the quantity of research into active and passive drag in swimming is substantial. Consequently, a review of literature on this topic has been synthesised. Moreover, the following review is focussed on the information considered pertinent to the present work: Underwater kicking following the turn in freestyle swimming.

In swimming, the measurement of passive drag is usually performed by towing a swimmer in a fixed streamlined position. A swimmer is streamlined when the frontal area striking the water during forward movement is minimised (Sanders & Stewart, 1992). Hence, passive drag is considered an indicator of gliding aptitude as it has been shown to vary with body position and inclination (Chatard, Bourgoin & Lacour, 1990; Chatard, Lavoie, Bourgoin & Lacour, 1990; Clarys et al., 1973; Clarys & Jiskoot, 1975; Costill, 1966; Karpovich, 1933; Kent & Atha, 1971; Kolmogorov & Duplishcheva, 1992; Kolmogorov, Rumyantseva, Gordon & Cappaert, 1997). Generally, the results of the many passive drag investigations demonstrate reliable findings (Chatard & Bourgoin et al., 1990; Chatard, Lavoie et al., 1990; Clarys, 1979; Hollander, de Groot, van Ingen Schenau, 1987; Karpovich, 1933; Kolmogorov & Duplishcheva, 1992; Kolmogorov et al, 1997).

Several methods have been used to estimate/measure active drag. These methods include indirectly estimating active drag from calculations based on changes in oxygen consumption (di Prampero, Pendergast, Wilson & Rennie, 1974; Holmer, 1974), by mathematically extrapolating force measurements from towed swimming (Clarys, 1979) and calculated from previously developed lift and drag coefficients combined with hand orientations measured from film analysis (Schleihauf et al., 1983). The development of the Measure of Active Drag (MAD-system) first enabled researchers to directly measure active drag during swimming (Hollander et al., 1986). More recently, Kolmogorov and Duplishcheva (1992) calculated active drag as a function of power output. Active drag values across these methods have yielded inconsistent findings. Indirect measurement methods suggest active drag is larger than passive drag (Clarys, 1978a; Clarys, 1978b; Clarys, 1979; di Prampero et al., 1974). Measurement of active drag using the MAD system however, showed active drag during front crawl swimming to be closer to previously reported passive drag values (Hollander et al., 1987; Hollander et al., 1986).

Further, Kolmogorov and Duplishcheva (1992) reported active drag values for freestyle, backstroke and butterfly to be significantly lower than for passive drag. The authors however, attributed this finding to the out-of -water recovery used in these strokes. The contrasting findings with respect to measurement of active drag further highlight the uncertainty regarding the relationship between passive and active drag in swimmers. This relationship therefore remains equivocal (Benjanuvatra, Blanksby & Elliott, 2001; Lyttle, 1999).

Traditional exits from a swimming turning motion incorporate both gliding (passive) and kicking (active) components. Lyttle (1999) states that at similar depths, the frictional component of drag remains the same for both active and passive drag, while the form and wave drag components vary depending upon whether the drag originates from passive or active movements. Therefore, to optimise turn exits, clearer understandings of the factors that contribute to passive and active drag are required. Hence, selected passive and active drag studies are reviewed and summarised.

Passive drag studies

The significance of passive drag to turn exits is highlighted by Chatard, Bourgoin et al. (1990) who claim that gliding during the start and turns corresponds to approximately 10 – 25 % of the total event, depending on the stroke and race distance. Minimising the deleterious effect of passive drag during gliding is therefore likely to decrease swim times. Empirical testing is required to determine the hydrodynamic drag experienced by a swimmer. This is due to problems in quantifying the flow characteristics around the human body, which in turn, render it difficult to estimate the effect of depth and velocity on drag, from hydrodynamic theory (Lyttle et al., 1998). A popular method for investigating drag forces in swimming has been to tow swimmers and measure the tension and force in the towing device as a representation of the swimmer's resistance.

Numerous studies have investigated the passive drag experienced by swimmers at various velocities, depths and body positions. With the exception of the data presented by Ria, Bernard, Falgairette & Roddier (1987), passive drag studies have shown that increased glide velocities correspond with increasing passive drag values (Alley, 1952; Benjanuvatra et al., 2001; Benjanuvatra et al., 2002; Clarys & Jiskoot, 1975; Clarys et al., 1973; Clarys et al., 1974; Counsilman, 1955; di Prampero et al., 1974; Jiskoot & Clarys, 1975; Karpovich, 1933; Kent & Atha, 1971; Maiello, Sabatini, Demarie, Sardella & Dal Monte, 1998; Miyashita & Tsunoda, 1978; Strojnik, Bednarik & Strumbelj, 1999; van Manen & Rijken 1975). Hence, an increase in velocity will lead to a concurrent increase in passive drag force, providing all other factors remain constant. The impact drag has on swimming performance is further emphasised given the reported exponential relationship between velocity and passive force (Karpovich, 1933; Rushall et al., 1994). The direct relationship between passive drag force and towing velocity has also been consistently demonstrated across a variety of glide positions (Counsilman, 1955; di Prampero et al., 1974; Karpovich, 1933; Lyttle et al., 1998; Maiello et al., 1998) and towing depths (Lyttle et al., 1998; Maiello et al., 1998).

Swimmer passive drag forces have been examined through a variety of glide and body positions, with a prone horizontal glide position (with the arms and legs extended) investigated most commonly (Alley, 1952; Benjanuvatra et al., 2001; Benjanuvatra et al., 2002; Chatard, Bourgoin et al., 1990; Chatard, Lavoie et al., 1990; Clarys, 1979; Clarys, 1985; Clarys et al., 1973; Clarys et al., 1974; Clarys & Jiskoot, 1975;

Counsilman, 1955; di Prampero et al., 1974; Jiskoot & Clarys, 1975; Karpovich, 1933; Kent & Atha, 1971; Kolmogorov & Duplishcheva, 1992; Kolmogorov et al., 1997; Lyttle et al., 1998; Maiello et al., 1998; van Manen & Rijken 1975; Miyashita & Tsunoda, 1978; Ria et al., 1987; van Tilborgh, Daly & Persyn 1983; Maiello et al., 1998). Whereas, the supine glide (Karpovich, 1933), the lateral and rolling glide positions (Counsilman, 1955; Lyttle et al., 1998) and longitudinally angled glides (Clarys, 1979; Clarys, 1985; Clarys & Jiskoot, 1975) have been explored to a lesser extent. More recently, investigators have examined the effect of drafting swimming (swimming directly behind another swimmer) on passive drag (Chatard, Chollet & Millet, 1998; Chatard & Wilson, 2003) and the impact of wearing swimming suits designed to decrease drag have upon passive drag (Benjanuvatra et al., 2002; Roberts, Kamel, Hedrick, McLean & Sharp, 2003).

Differences in passive drag have also been reported for changes in head position (Alley, 1952; Karpovich, 1933; Kent & Atha, 1971; Miyashita & Tsunoda, 1978), arm and hand position (Maiello et al., 1998) and at various body inclinations (Alley, 1952; Clarys et al., 1973; di Prampero et al., 1974; Clarys & Jiskoot, 1975; Karpovich, 1933). With the exception of the report of Clarys and Jiskoot (1975), positional changes from a prone horizontal glide (streamline) position have consistently produced greater passive drag forces. Clarys and Jiskoot (1975) reported significantly less resistance occurred for a 45^{o} lateral glide position compared to the prone position, for towing velocities of 1.5 and 1.6 $m.s^{-1}$. However, significant differences in drag were not observed between the two glide positions for towing velocities above 1.6 $m.s^{-1}$ and were reversed at the fastest velocity (1.9 $m.s^{-1}$). Given the subjective opinion of some coaches, that lateral streamlined glide wall exits produce faster turn exits, Lyttle et al. (1998) suggest there may be a learning effect associated with the lateral position. That is, the ability to perform and maintain lateral streamline gliding may improve with practise, which may partially account for the contrasting finding by Clarys and Jiskoot (1975).

Measurement of passive drag at different depths has also revealed contrasting results. Hydrodynamic studies of streamlined objects indicate that drag is greatest immediately below the water surface, and decreases with greater depth (Blake, 1983; Hertel, 1966; Larsen et al., 1981). The findings from recent investigations of the effect of passive drag upon swimming performance (Benjanuvatra et al., 2002; Lyttle et al., 1998; Maiello et al., 1998) are in agreement with this previously developed fluid dynamic theory. Conversely, Clarys et al. (1974), Jiskoot and Clarys (1975) and Clarys (1979) demonstrated greater drag at 0.6 m underwater than that recorded at the surface. Attempting to explain this finding, Jiskoot and Clarys (1975) suggested that the combined frictional and eddy resistance when immersing the body in water was greater than the extra wave making resistance resulting from a partially submerged body. However, given that wave drag increases with the cube of swimming velocity, the low glide velocities used by Jiskoot and Clarys (1975) may not have been fast enough to create substantial wave drag. Also, the absence of information and subsequent lack of definition regarding towing depth may indicate variability in methodologies, which is likely to have contributed to the inconsistent findings in these earlier studies.

Maiello et al. (1998) investigated the passive drag on the surface and 0.5 m underwater at two separate water velocities, in a swimming flume at water velocities of 1.76 & 1.91 $m.s^{-1}$. Eleven female swimmers performed prone streamline gliding and five separate upper body positions at each depth and velocity. Results indicated lower underwater passive drag values for all body positions, and at both velocities, compared with the surface trials. Despite the fact that no statistical procedures were applied to the data in order to establish statistical significance of the observed differences, this study indicates that greater economy is achieved by a swimmer from gliding at 0.5 m underwater compared with at the surface, due to reduced passive drag. Lyttle et al. (1998) and Benjanuvatra et al. (2002) have since published data in support of this finding by demonstrating that a statistically significant difference exists between surface and underwater passive drag values in swimmers. These recent studies that have explored passive drag during swimming suggest that the increased frictional and form drag created by submerging the body is negated by a greater reduction in wave drag.

Changes in water temperature have also been shown to contribute to drag measured when towing swimmers (Clarys, 1979; Clarys & Jiskoot, 1975). Increased water temperature leads to lower water density and viscosity, which in turn, decreases passive drag values (Videler, 1993). This finding may affect any comparison of absolute drag values, both within and between drag investigations. Therefore, maintenance of a constant pool water temperature throughout towing and other swimming studies is necessary to uphold the internal and external validity of the findings.

The majority of early passive drag studies examined swimmer resistance at velocities representative of free-swimming velocities (range: 0.31 – 2.13 $m.s^{-1}$). However, velocities ranging between 1.9 – 3.1 $m.s^{-1}$ are more closely associated with the gliding velocities experienced by swimmers following a start or wall push-off from a turn (Albrand & Walter, 1975; Benjanuvatra et al., 2001; Blanksby, Gathercole et al., 1996; Larsen et al., 1981; Lyttle et al., 1999). Hence, the application of passive drag findings from studies that used velocities designed to reflect free-swimming to the specific velocities found during the turn glide phases is limited. Furthermore, insufficient descriptions of methodological and statistical procedures limit interpretation of the validity of the findings from these investigations.

Lyttle et al. (1998) sought to address this disparity by measuring swimmer drag at towing velocities more representative of the glide during starts and turns. They examined drag forces when towing 40 experienced male swimmers of similar body shape, mass and height through water at pre-determined depths and velocities. Swimmer depth was defined using the mid-line of the frontal plane when towed in a prone, streamlined position. A load cell was used to measure drag at the surface, 0.2, 0.4 and 0.6 m below the surface and at selected velocities ranging between 1.6 and 3.1 $m.s^{-1}$. During towing, swimmers wore caps and maintained a prone, streamlined position, with the hands overlapping, head between the extended arms, and the feet together and plantar flexed. Practice trials were permitted at different velocities and depths, while towing depths and velocities were randomised during testing. During the towing trials, the depth level, degree of streamlining and whether a horizontal position was assumed were assessed via real time images from underwater video. Swimmers were given this feedback and test trials were repeated if the swimmer was not within ± 0.05 m of the set depth, or was not in a horizontal position. Water temperature was maintained at 28^{o} C (± 0.6 ^{o} C).

Significantly ($p<0.05$) higher passive drag was observed at the surface than for each increasing depth, across all towing velocities (Lyttle et al., 1998). No significant differences in drag were observed between the 0.2, 0.4 and 0.6 m depths for the two slowest velocities (1.6 & 1.9 $m.s^{-1}$). Whereas, the drag at 0.2 m was significantly higher than the drag recorded at the 0.4 and 0.6 m depths for the remaining velocities (2.2 – 3.1 $m.s^{-1}$). The 0.4 and 0.6 m depths revealed no significant difference in drag force. These findings concur with previous hydrodynamic studies that showed the highest drag force for a streamlined cylindrical body is recorded just below the water surface (Hertel, 1966) and that the coefficient of drag decreases rapidly as a body increases in depth (Larsen et al., 1981).

The findings by Lyttle et al. (1998) are in agreement with previous passive drag investigations that demonstrate increasing passive drag values with increased towing velocity (Alley, 1952; Benjanuvatra et al., 2001; Benjanuvatra et al., 2002; Clarys & Jiskoot, 1975; Clarys et al., 1973; Clarys et al., 1974; Counsilman, 1955; di Prampero et al., 1974; Jiskoot & Clarys, 1975; Karpovich, 1933; Kent & Atha, 1971; Maiello et al., 1998; Miyashita & Tsunoda, 1978; van Manen & Rijken 1975). However, Lyttle et al. (1998) unexpectedly demonstrated a linear, rather than exponential relationship from drag force-velocity curves over the velocity range tested. This varies from the relationships demonstrated in hydrodynamic studies using streamlined objects (Hertel, 1966; Larsen et al., 1981). Passive drag findings from other non-streamlined human form studies were inconclusive as they showed either a linear or exponential trend (Kent & Atha, 1971; Clarys, 1979; Jiskoot & Clarys, 1975). Many of these investigations into drag during swimming have questionable methodologies or fail to accurately report the degree of association (linear or exponential). Extrapolating the drag force data to zero or investigating the drag at higher velocities may in fact reveal an exponential relationship for passive drag values with increased towing velocity. Nonetheless, over a velocity range representing turn push-off and glides for club to elite level swimmers, Lyttle et al. (1998) demonstrated a linear increase in passive drag force with an increase in glide velocity.

A reduction in passive drag during gliding following a turn will translate directly to faster turn times. With the exception of Lyttle et al. (1998), the application of findings from earlier studies that have examined passive drag to turn performance is limited due to the majority of these investigations being performed either at the water surface or at lower velocities than those experienced following a turn. From their findings, Lyttle et al. (1998) mathematically modelled an optimal glide path for maximising a swimmer's horizontal glide velocity from wall push-off following a turn (see Figure 2.3). Calculated from the theoretical deceleration times and glide distances, this optimal path consisted of the swimmer pushing off the wall at 3.1 $m.s^{-1}$, approximately 0.4 m underwater and maintaining this depth for a glide distance of approximately 1 m (in approximately 0.4 s). Thereafter, gradual ascent over a further 1 m distance, at a rate of 0.1 m in depth per 0.2 s, at which time the swimmer would resume stroking at the surface at 1.6 $m.s^{-1}$ (Lyttle, 1999).

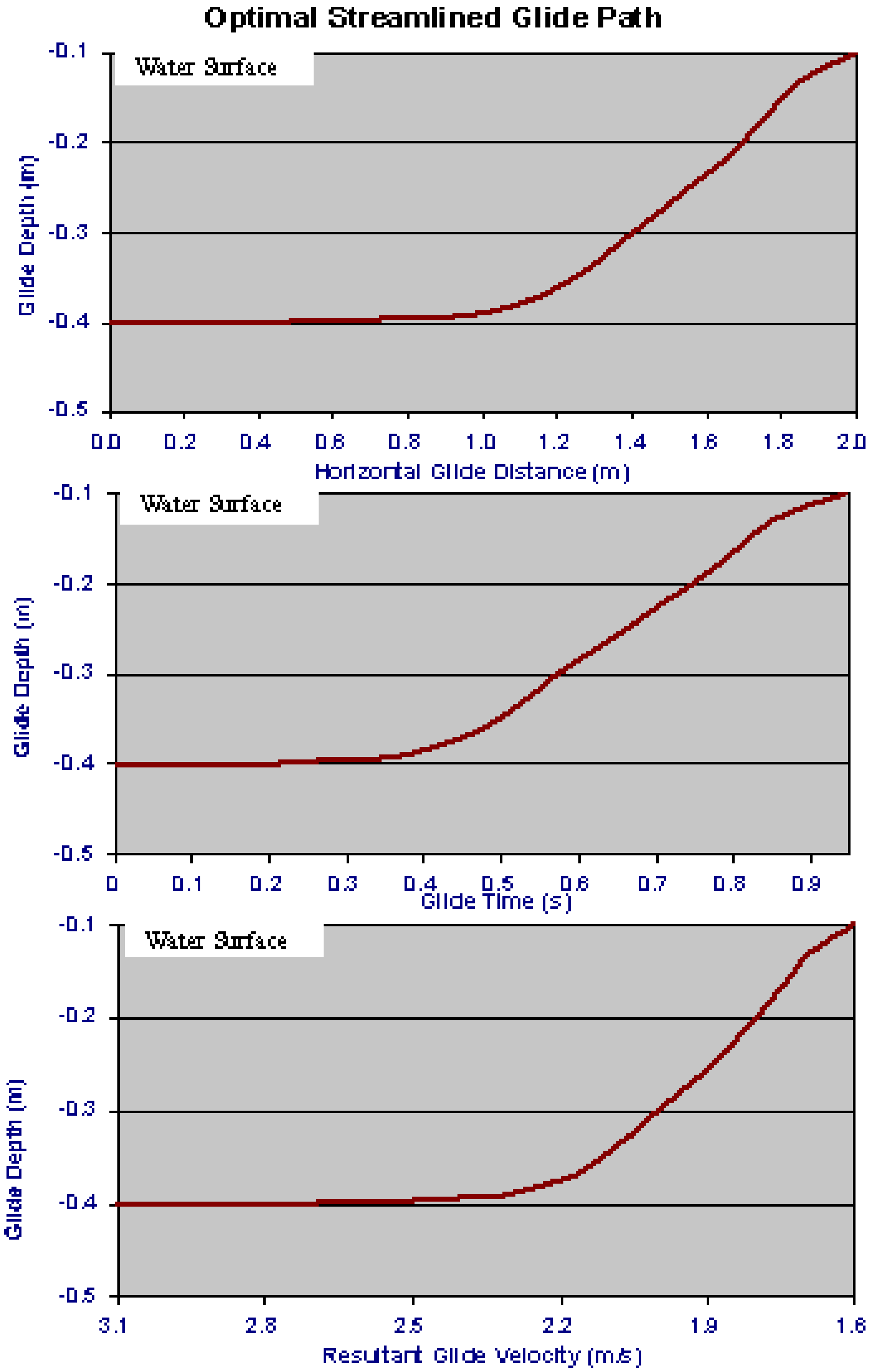

Figure 2.3. Optimal glide depth vs. glide distance, time and resultant velocity (From Lyttle, 1999, p. 114).

Human morphology and passive drag

Experiments with water mammals have examined the relationship between the morphological characteristics of the body and its efficiency of movement through water (Clarys, 1979). Similarly, fundamental hydrodynamic theory, developed from ship building research, indicates drag force is determined partly by body form (Larsen et al., 1981). Several investigations have reported the influence of body form on the passive drag experienced by a swimmer (Benjanuvatra et al., 2001; Chatard, Bourgoin et al., 1990; Chatard, Lavoie et al., 1990; Clarys, 1978a, 1978b, 1979, 1985 & 1986; Clarys, Jiskoot, Rijken & Brouwer, 1974; Lyttle et al., 1998; Miyashita & Tsunoda, 1978; Ria et al., 1987; van Manen & Rijken 1975; van Tilborgh et al., 1983). From these investigations, numerous body form parameters have been found to influence passive drag. However, the findings of these investigations exhibit conflicting results.

The effect of human body form on swimming passive drag was pioneered by Clarys and associates (Clarys, 1978a, 1978b, 1979, 1985 & 1986; Clarys et al., 1974). Using data obtained from the extensive work of Clarys, Lyttle (1999) detailed a series of body form parameters, based upon fundamental hydrodynamic principles, to provide a link between swimming and the form parameters used in ship design (see Table 2.2). To date, several body form parameters have been consistently shown to influence passive drag. In particular, these parameters include body cross-sectional area, height and weight (Benjanuvatra et al., 2001; Chatard, Bourgoin et al., 1990; Chatard, Lavoie et al., 1990; Clarys, 1978a, 1978b & 1979; Ria et al., 1987; van Tilborgh et al., 1983). However, several investigations present conflicting findings regarding other body forms and passive drag. Early investigations by Clarys (1978a & 1978b) demonstrated a non-significant relationship between the passive drag force and body surface area. These data were supported by several subsequent investigations (Clarys, 1979, 1986; Lyttle et al., 1998; Miyashita & Tsunoda, 1978). These results suggest frictional resistance is proportionately low in human hydrodynamics, which is in direct contrast to fundamental hydrodynamic principles (Gadd, 1963; Karpovich, 1933).

Clarys (1978a) suggested that fluid flow around a towed human body is turbulent and that the frictional drag component, which is predominantly a function of laminar flow, is likely to be minimised. This was alleged to account for a lack of relationship between surface area and passive drag (Clarys, 1978b & 1986). Conversely, a number of investigations have reported strong relationships between body surface area and passive drag (Chatard, Bourgoin et al., 1990; Chatard, Lavoie et al., 1990; Ria et al., 1987; van Tilborgh et al., 1983). Fundamental hydrodynamic principles indicate that for streamlined and geometric bodies, increases in frictional drag are directly related to increases in the wetted body surface area (Gadd, 1963). It is possible that the use of total body surface area may inappropriately represent the wetted body surface area of a swimmer when towed at the water surface (only partially submerged). The findings from Lyttle et al. (1998) refute this theory as their study demonstrated that body surface area did not have a significant influence on passive drag when the body was towed at the water surface and at depths of 0.2, 0.4 and 0.6 m.

In general, the relationship between body shape and passive drag has typically been shown to increase with increasing glide velocity (Clarys, 1979; Lyttle et al., 1998). In addition, body cross-sectional area, height and weight have been significantly related to passive drag force in swimmers (Benjanuvatra et al., 2001; Chatard, Bourgoin et al., 1990; Chatard, Lavoie et al., 1990; Clarys, 1978a, 1978b & 1979; Ria et al., 1987; van Tilborgh et al., 1983). Furthermore, significantly lower passive drag forces have been observed in hyper flexible swimmers (Chatard, Lavoie et al., 1990), indicating that by increasing the degree of joint flexibility, a swimmer may be able to achieve a more streamlined glide position and decrease resistive passive drag. Despite identification of the above associations, the relationships between human morphology and passive drag remain unclear and require further empirical testing.

Table 2.2. Human morphology equivalents of fundamental hydrodynamic parameters.

Hydrodynamic parameters	**Human morphology Equivalents**	**Drag component**
Body length	Body height	Wave drag
Wetted area	Body surface area (wetted)	Frictional drag
Mid-ship section	Greatest body cross-section	Form drag
Buoyancy	Hydrostatic weight, body volume, body density	Form drag
Length/Breadth ratio	Body height/Biacromial breadth	Form drag
Length/Depth ratio	Body height/Thorax depth	Frictional drag
Length/Thickness ratio	Body height/Greatest body cross-section	Form drag
Length/Surface ratio	Body height^2/Body surface area	Frictional drag
Slenderness degree	Body height/Body volume$^{1/3}$	Wave drag
Breadth/Depth ratio	Biacromial breadth/Thorax depth	Form drag

From Lyttle (1999, pp. 60), originally adapted from Clarys et al. (1974, p.188) and Clarys (1979, p.21).

Active drag studies

Active drag results from movements produced by the swimmer, usually when attempting to increase propulsion from kicking or stroking. The majority of studies that have examined active drag have attempted to determine the drag created by a swimmer during freestyle swimming (Alley, 1952; Cappaert, Kolmogorov, Walker, Skinner, Rodriguez & Gordon, 1996; Clarys, 1979 & 1985; Clarys et al., 1973; Counsilman, 1955; di Prampero et al., 1974; Glazkov & Dementyev, 1977; Hollander et al., 1986; Holmer & Haglund, 1978; Huijing, Toussaint & Clarys, 1988; Kemper, Verschuur, Clarys & Jiskoot, 1983; Kolmogorov & Duplishcheva, 1992; Kolmogorov et al., 1997; Kugovnik, Bednarik, Strumbelj & Kapus, 1998; Moghadam, Mehrvar & Pazouki, 1996; Niklas et al., 1993; Toussaint, de Groot, et al., 1988; Toussaint & Hollander, 1994; Toussaint, Hollander, et al., 1988; Toussaint, de Looze, Van Rossem, Leijdekkers & Dignum, 1990; Takagi, Shimizu, Kodan, Onogi & Kusagawa, 1997). Whereas measurement of active drag for the other strokes (Kolmogorov & Duplishcheva, 1992; Kolmogorov et al., 1997), during kicking (Benjanuvatra et al., 2002; Lyttle et al., 2000) and when various swimming suits are worn (Benjanuvatra et al., 2002; Toussaint, et al., 1989; Toussaint et al., 2002), have been explored to a lesser degree. Aside from methodological issues, the findings from studies that have examined active drag during stroking bear little significance to the present work that is focused upon underwater kicking following the turn in freestyle swimming. Therefore, the following review is limited to brief descriptions of the measurement of active drag and is focussed upon those studies considered pertinent to the current project.

A variety of methods have been used to examine active drag during swimming. Alley (1952) and Counsilman (1955) incorrectly determined active drag as the difference between the total effective propulsive force during active movements and the prone passive drag force, for a given velocity. This method falsely assumed that the passive drag during prone streamlining is equivalent to the active drag created during stroking. di Prampero et al. (1974) pioneered a method of indirectly determining active drag through changes in the rate of oxygen consumption (VO_2), recorded from swimming at constant velocities with different drag loads. Known weights attached to the swimmer via a rope and pulley system were incrementally added to swimmers moving at constant velocity. Changes from baseline resting VO_2 were recorded and expressed as a function of active drag. Despite other active drag studies employing this method (Holmer & Haglund, 1978; Niklas et al., 1993), this method is complicated and may be likely to exhibit poor reliability.

The extensive work by Clarys and associates (Clarys et al., 1973; Clarys, 1978a, 1978b & 1985; Kemper et al., 1983) determined active drag by estimating the effective drag produced during towed swimming. This method involved towing participants, while swimming, through a range of velocities and measuring the force in a towing carriage. A net positive force indicated that the swimmer generated higher active drag forces than the propulsive forces produced while swimming at a given velocity. A net zero force indicated the propulsive force equalled the resistive force. That is, the swimmer needed to be able to maintain the velocity of the towing carriage for this to occur. A net negative force demonstrated that the swimmer produced more propulsive force than the amount of active force created due to stroking. A curve was then fitted to the forces recorded at each of the towing velocities and extrapolated to zero velocity. The extrapolated force at zero velocity was added to the original curve to obtain the swimmer's active drag. Though widely recognised and used or adapted in various other drag studies (Glazkov & Dementyev, 1977; Takagi et al., 1997; van Manen & Rijken, 1975), this method assumes that the velocity range tested is representative of the drag-velocity effects at lower towing velocities (Lyttle, 1999).

Hollander et al. (1986) developed the Measure of Active Drag (MAD-system) that first enabled researchers to directly measure active drag during swimming. This system used a dynamometric approach where swimmers applied force against underwater paddles, during the underwater pull-phase of front crawl stroking (see Figure 2.4). A uni-directional strain gauge force transducer contained at one end of the system was used to record force in the direction of the travelling swimmer. Hence, at constant swimming velocity, the mean propulsive force applied to the paddles is considered equivalent to the average drag force. Despite repeated trials on a single subject demonstrating system reliability (Hollander et al., 1986) and its use in several subsequent investigations (Huijing et al., 1988; Niklas et al., 1993; Toussaint, de Groot et al., 1988; Toussaint & Hollander, 1994; Toussaint, Hollander et al., 1988; Toussaint et al., 1990), the MAD-system is limited to investigations involving arm-stroking only.

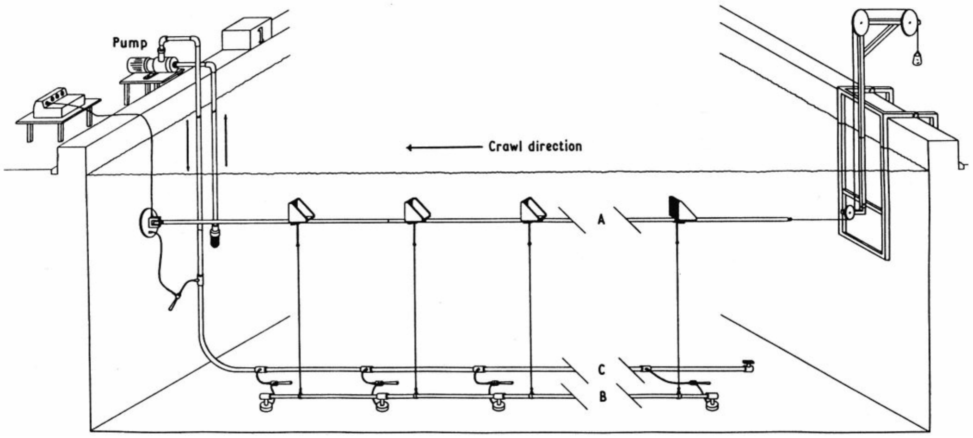

Figure 2.4. Schema of the Measurement of Active Drag (MAD) system (From Hollander et al., 1986, p. 23)

Kolmogorov and Duplishcheva (1992) calculated active drag as a function of power output. In this method, a hydrodynamic body creating a known additional drag is attached behind the swimmer. The maximal velocity when swimming with the hydrodynamic body is then compared with maximal free-swimming velocity. From these velocities, and the assumption that the swimmer is capable of delivering a constant mechanical power output (Kolmogorov & Duplishcheva, 1992), the active drag force is calculated. Errors due to intra-cycle velocity fluctuations have been modelled to represent between 6 – 8 %.

Active drag values derived during swimming have yielded inconsistent findings across a range of investigations. Indirect methods of estimating active drag have shown active drag to be larger than passive drag (Clarys, 1978a, 1978b & 1979; di Prampero et al., 1974), while the use of mathematical models (Moghadam et al., 1996) to calculate active drag force have demonstrated substantially higher values than the MAD-system (Hollander et al., 1986) or from film analysis (Schleihauf et al., 1983). Front crawl active drag values using the MAD-system have been shown to be closer to previously reported passive drag values (Hollander et al., 1986; Hollander et al., 1987). Conversely, active drag values for freestyle, backstroke and butterfly have been reported to be significantly lower than for passive drag (Kolmogorov & Duplishcheva, 1992). These contrasting findings observed across active drag investigations are likely to be due, in part, to the various research designs and methods used to calculate active drag.

Few investigations have been located that report the active drag created during kicking (Alley, 1952; Lyttle et al., 2000; Thrall, 1960). Alley (1952) compared the active drag effects for one elite male swimmer who used typical and reduced amplitude flutter kicking techniques. Both kicks were regulated by an audible signal to ensure the same six beat kick frequency, however, the difference in amplitude between the two kick actions was not reported. Attaching a web belt to the swimmer and measuring the force exerted at given velocities as they swam away from the apparatus enabled calculation of surplus propulsive force. The towing force was measured over a range of velocities, each of which was greater than maximal free-swimming velocity recorded for the associated stroke type. This was achieved by measuring the force required to tow the swimmer toward the apparatus while kicking. The results indicate that for velocities ranging up to the swimmer's maximal kicking velocity for each kicking action, net force benefits for the typical flutter kick were consistently higher than the reduced amplitude flutter kicking action (Alley, 1952). Similarly, the typical flutter kick required a smaller towing force than the reduced amplitude flutter kick for velocities exceeding their maximal free-kicking velocities. Therefore, this case study indicates that a typical flutter kick provides a net force benefit over a reduced amplitude flutter kick, for the velocity range tested.

Thrall (1960) examined the effect that the size and shape of the feet and kick frequency have on the propulsive force during flutter kicking. Free-swimming velocities were obtained from three male intercollegiate swimmers who each performed a typical flutter kick (6 beat kick), a reduced amplitude flutter kick (2 beat kick), and from kick trials performed while using wide and narrow fins (with the same effective surface area). Baseline drag data were also obtained from six towing velocities ranging from 0.91 $m.s^{-1}$ to 2.42 $m.s^{-1}$ conducted while the subjects were in a prone streamlined gliding position, and also when wearing the narrow and wide fins. Towing force data were then recorded from trials consisting of each of the four kicking conditions, at these same six towing velocities.

Thrall (1960) defined the effective propulsive force of the kick as the difference between the towing force and the passive drag, at any given velocity. Despite this questionable approach to determining propulsive force, descriptive analyses indicated that participant's attained greater free-swimming velocity and greater effective propulsive force during typical flutter kicking than when using the reduced amplitude flutter kick (Thrall, 1960). The fin swimming conditions produced a mean increase in both the free-swimming velocity and the effective propulsive kick force for both kicking styles. This finding indicates that swimmers who have greater foot surface area may have the potential for greater kicking aptitude.

The kicking studies by Alley (1952) and Thrall (1960) were performed at the water surface and only represent the performances of one and three subjects, respectively. Kicking following the glide phase from turns creates active drag forces under the water surface. Given the recent findings of Lyttle et al. (1998) and fundamental hydrodynamic theory (Hertel, 1966; Larsen et al., 1981) regarding effects of depth on passive drag force, an examination of active drag during underwater kicking was necessitated.

The study by Lyttle et al. (2000) represents the first study that examined the active drag experienced during underwater kicking. Sixteen experienced male swimmers of similar body shape were towed along the length of a 25 m pool at a depth of 0.5 m underwater, at each of five different velocities (1.6; 1.9; 2.2; 2.5 & 3.1 $m.s^{-1}$), using a mechanical winch system. These velocities were deliberately chosen to represent the push-off and glide velocities demonstrated by club and elite level swimmers following a turn (Lyttle et al., 2000). Towing depth was defined from the lateral view by using the mid-line of the body and controlled using a two-pulley system that was fixed to the pool wall. At each velocity, subjects performed prone and lateral streamlined glides, prone freestyle and dolphin kicking, and lateral dolphin kicking.

All kicking trials were performed with maximal effort and no limitation was placed on kick amplitude. Net force was recorded during each trial using a uni-directional load cell. For the prone and lateral streamlined trials, the net force consisted solely of the negative passive drag forces. Whereas during the kicking trials, net force consisted of the total propulsive force measured during kicking minus the active drag force created during the kicking action. Hence, a positive net force would indicate that a swimmer was accelerating as a result of kicking.

Lyttle et al. (2000) found no difference in net towing force between the prone and lateral streamlined glides at all of the velocities tested. Similarly, neither kick strategy resulted in a significant advantage over the other. However, trends in the data indicated the prone dolphin kick consistently produced lower net forces than the freestyle and lateral dolphin kick conditions. Results from 2-way repeated measures ANOVA revealed significant velocity-by-towing condition interactions (Lyttle et al., 2000). At the lower velocities (1.9 & 2.2 $m.s^{-1}$), post-hoc comparisons revealed the streamline positions recorded significantly higher net forces than the kicking conditions, indicating a benefit to the swimmer from kicking at these velocities. When towed at 2.2 $m.s^{-1}$, net forces in the prone streamline position were not significantly different from the kicking conditions, suggesting that there is no advantage for the swimmers to kick at this velocity. No post-hoc comparisons were performed at the 2.5 $m.s^{-1}$ velocity due to no significant differences being observed between any of the towing conditions. A reversal of these trends was demonstrated at the highest velocity (3.1 $m.s^{-1}$) where the prone streamline position produced significantly lower net forces than kicking. This indicated that kicking at this velocity was detrimental to the swimmer. At no time did any swimmer produce a positive net force at any velocity, indicating they were not able to kick faster than the towing speed.

Based on the results from an earlier investigation, Lyttle et al. (1998) modelled an optimal glide path for maximising a swimmer's horizontal glide velocity from wall push-off following a turn (see Figure 2.3). The findings from this more recent work enabled preferred kicking resumption velocity to be determined by identifying the highest velocity at which underwater kicking produces less net drag force than the streamline position (this velocity has been defined as the cross-over velocity). In consideration of this finding and the earlier proposed optimal glide path, Lyttle et al. (2000) suggested a hypothetical optimal glide and kicking path for maximising horizontal velocity from wall push-off to the resumption of stroking, following a turn (see Figure 2.5). Within this adapted wall exit strategy, Lyttle et al. (2000) determined that for experienced male swimmers, kick resumption should occur between the velocities of 2.2 and 1.9 $m.s^{-1}$ as it is beneficial to kick rather than maintain a streamlined glide at velocities below this range. This velocity range was found to coincide with the period just after which swimmers should begin to ascend to the surface and equates to between approximately 1.1 and 1.5 m, or between 0.45 and 0.65 s, of gliding (see Figure 2.5). The authors state however, that this model is speculative and relies on the relationships between the glide and kicking positions, as well as the cross-over velocity, remaining constant.

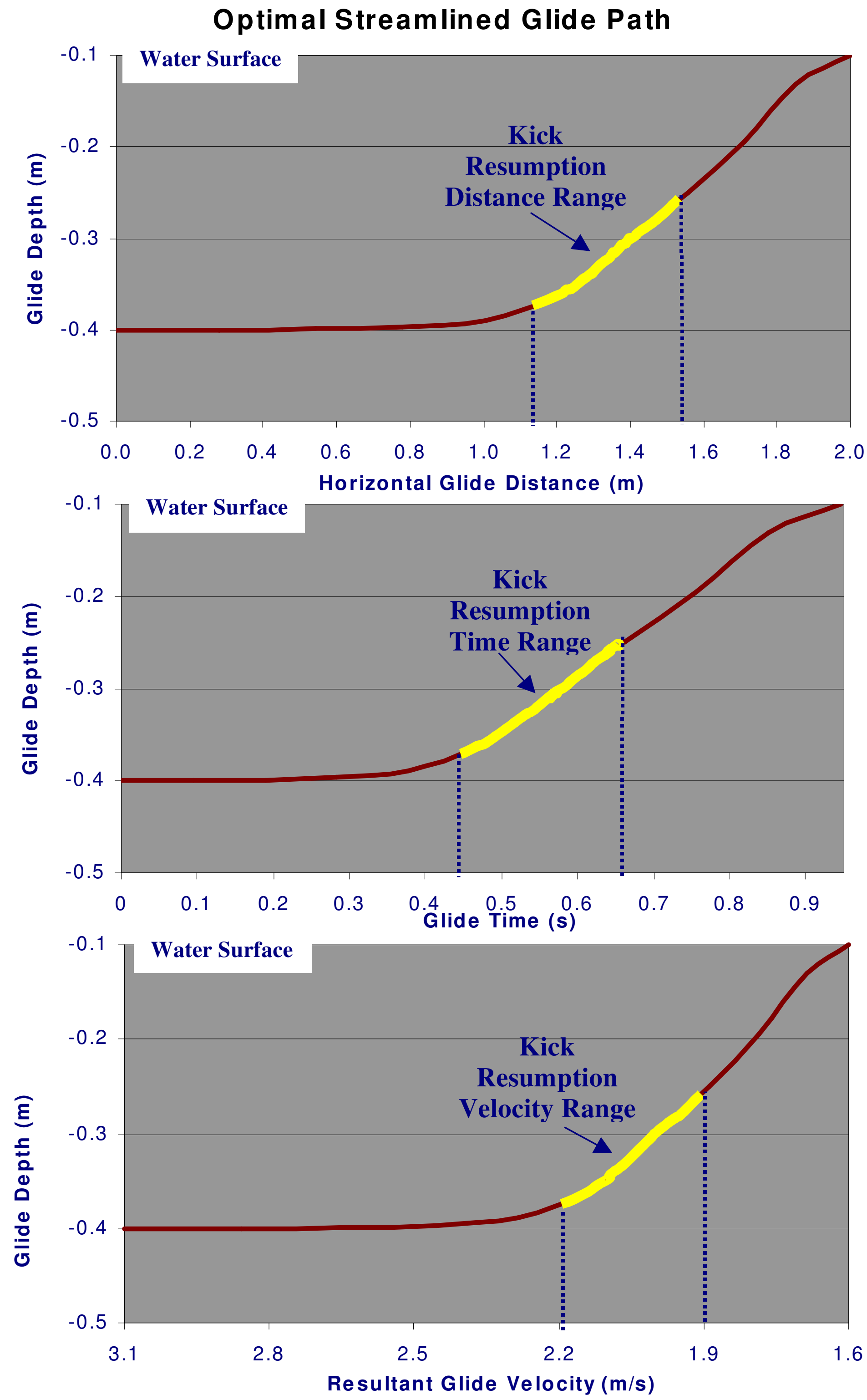

Figure 2.5. Hypothetical optimal streamlined gliding and kicking path (From Lyttle, 1999, p. 129)

Sanders and Byatt-Smith (2003) mathematically modelled a formula to assess wall exit strategies based on deceleration rates from streamline gliding. Application of this model to the turns of experienced swimmers indicated that in many cases, kicking is initiated too soon. It was found that flexion of the knees during preparation for kicking was notably detrimental to horizontal velocity. Additionally, kicking failed to restore velocity equivalent to that which would have been sustained had swimmers maintained a streamlined glide without the kick (Sanders & Byatt-Smith, 2003). Despite the fact that their article contained no statistical analyses and failed to report the kick styles used (flutter or dolphin), Sanders and Byatt-Smith (2003) suggest that kicking too early following the turn is common, reduces velocity and wastes energy unnecessarily.

The findings from Lyttle et al. (2000) and Sanders & Byatt-Smith (2003) highlight the importance of selecting the optimum time to initiate underwater kicking following the start and turn. When kicking too soon after wall push-off, the extra drag generated by deviating from a streamline position is likely to counter any propulsive force from kicking (Lyttle & Benjanuvatra, 2004). On the contrary, inappropriately delaying the initiation of underwater kicking will not allow the swimmer to maximise the full benefits underwater kicking can provide. Current research shows that most swimmers should wait for approximately 1 s before initiating underwater kicking (Lyttle et al., 2000; Sanders & Byatt-Smith, 2003). Despite many swimmers preferring to use underwater dolphin kick following the turns, underwater kicking styles have not been investigated conclusively. From measurements of active drag during towing, Lyttle et al. (2000) were unable to determine the most efficient underwater kicking style (flutter, prone and lateral dolphin) and concluded that swimmers should choose the technique at which they are most proficient. Although their investigation demonstrated a trend favouring the prone dolphin kick, the magnitude (large, small) and speed (fast, slow) of kicking was not delimited or investigated. Hence, the superior underwater kicking style and technique for use following turns remains unknown, and is in need of further investigation.

Human morphology and active drag

Like the results from passive drag investigations, studies examining the relationship between body form and active drag reveal contrasting findings. A variety of methods have also been used to determine active drag in swimming. These methods include indirect calculation (Clarys, 1978a, 1978b, 1979 & 1986), direct measurement using the MAD-system (Huijing et al., 1988; Toussaint et al., 1990), estimations based on the additional hydrodynamic body technique (Kolmogorov and Duplishcheva, 1992; Kolmogorov et al., 1997) and computational techniques (Cappaert & Gordon, 1998). Not surprisingly, it is likely that much of the disparity in the data arising from an exploration of the relationship between human morphology and active drag due to the variety of study designs and methods used in these investigations.

Using an indirect method of calculating active drag (extrapolating the drag force curve to zero velocity), Clarys and associates (1978a, 1978b, 1979 & 1986) demonstrated little association between body form parameters and active drag force. For example, despite demonstrating similar passive drag values, active drag during front crawl swimming was found to be much lower for Olympic level compared with non-swimmers (Physical education students). Collectively, these authors concluded that due to a lack of a significant relationship between body form parameters and active drag force, body shape exerts very little influence on the drag created when swimming.

Further, they stated that active drag is a consequence of changes in body shape caused by the movement of body segments, and is therefore largely dependant upon swimming technique. Kolmogorov and Duplishcheva (1992) and Kolmogorov et al. (1997) also concluded that individual swimming technique has a greater influence on active drag than body shape. This conclusion was made from data collected using the additional hydrodynamic body technique to estimate hydrodynamic drag across a variety of swimmers (varying genders and performance levels) and strokes. Although Kolmogorov and Duplishcheva (1992) and Kolmogorov et al. (1997) failed to statistically compare active drag data with anthropometric measures, they reported a non-significant correlation between the active and passive drag force coefficient, and a large variance in the active drag force coefficient between subjects.

In contrast, Huijing et al. (1988) used the MAD-system to calculate active drag and found significant correlations to exist between numerous anthropometric variables and active drag. These variables included maximum body cross-sectional area, body mass, height and various body widths, lengths and circumferences. This finding was not, however, corroborated by Toussaint et al. (1990) who also used the MAD-system to quantify active drag. Their investigation differed from those conducted previously in that changes in active drag were investigated over a 2.5-year period. This longitudinal study examined the active drag of four male and nine female adolescents during freestyle swimming at different but constant velocities ranging between 0.8 to 1.6 $m.s^{-1}$. Toussaint et al. (1990) found that for any given velocity, no difference in active drag was observed despite swimmers demonstrating an 11 % increase in height, 37 % increase in weight and a 16 % increase in body cross-sectional area. Significant increases were also observed in the length/depth, length/thickness and width-depth body form ratios, indicating the swimmer's bodies became more streamlined with age. In addition, only selected anthropometric parameters were found to correlate with active drag, although these relationships were not consistent across the different testing sessions.

Toussaint et al. (1990) postulated that the lack of change in active drag over the duration of the study was due to a decrease in wave-making resistance. These authors reasoned that in accordance with Froude number theory, increased swimmer height resulted in a decrease in the Froude number, which subsequently resulted in decreased wave-making resistance. This hypothesis was supported by presenting the same drag data against the Froude number, which effectively corrected for the change in height. These new data confirmed that an increase in drag had occurred but was masked by changes in height. Toussaint et al. (1990) reported a 14 % improvement in swimming performance (~10 s reduction in average 100 m time) indicating changes in stroke mechanics; increased skill and streamlining ability were present. Therefore, the lack of change in active drag may have resulted from changes in swimming technique, as indicated in other investigations (Clarys, 1986; Kolmogorov & Duplishcheva, 1992, Kolmogorov et al., 1997; Toussaint, Beelen, et al., 1988).

Despite investigations being conducted by numerous authors (Cappaert & Gordon, 1998; Clarys, 1978a, 1978b, 1979 & 1986; Huijing et al., 1988; Kolmogorov and Duplishcheva, 1992; Kolmogorov et al., 1997; Lowensteyn, Signorile & Glitz, 1994; Toussaint et al., 1989; Toussaint et al., 1990), a consistent relationship between body form and active drag during swimming has not been established. Trends evident in these findings suggest swimming technique plays a greater role in active drag than body form measures, although this concept remains equivocal. The variety of methods used to determine active drag is likely to have contributed to the disparity in findings. In keeping with the findings presented for passive drag, the majority of investigations examining the relationship between body form and active drag have been conducted predominantly during stroking, and at the water surface. Subsequently, information is lacking regarding the affect body form has on active drag during underwater swimming and kicking. Further research is therefore needed in this area.

Underwater kicking and freestyle turns

While research into turns can be dated back to the 1950s (King & Irwin, 1957), this area of study has progressed marginally in comparison to the volume of research that has investigated aspects of stroking. Blanksby (1999) cited difficulty in measuring key variables underwater, the lack of underwater viewing windows and an absence of underwater force platforms as probable reasons for this dearth of inquiry. However, technological advancements, in conjunction with several authors highlighting the importance of turns in overall swim performance (Maglischo, 1993; Thayer & Hay, 1984), has resulted in greater interest and the steady development of turning research. One aspect of swimming turns that remains relatively unexplored is the underwater kick phase in freestyle swimming. Despite some researchers focusing on underwater kicking, determination of optimal underwater kicking strategies and techniques for use during freestyle turns remains equivocal.

Early swim kicking studies were conducted at the water surface and by either isolating the kick or from within whole stroke swimming (Alley, 1952; Barthels & Adrian, 1971; Bucher, 1975; Cavill, 1973; Jensen & McIlwain, 1979; Kelly, 1973; Sheeran 1980; Ungerechts, 1983a). Application of the findings from within-stroke kicking studies to the present work is potentially limited due to the arm stroke often governing the kick rate and amplitude. Similarly, application of the findings from surface kicking-only studies to the current investigation is likely to be limited due to altered hydrodynamic effects. That is, variations in drag due to increased wave resistance generated at the surface (Hertel, 1966; Larsen et al, 1981; Lyttle et al, 1998) and an inability to apply propulsive force when the feet break the water surface are likely to restrict the relevance of findings to kicking underwater. In addition, provision of insufficient methodological and statistical detail in the published reports limits the validity of findings from some of these investigations. For the purpose of this review, reference to the results from surface and in-stroke kicking studies is therefore confined to those results deemed pertinent to the present investigation and are considered with respect to the limitations identified.

For many years, freestyle swimmers have executed a bi-lateral, single leg vertical kicking action (flutter kicking) following the turn and prior to resuming the stroke. This kick technique represents that used during stroking and was widely considered to be beneficial only in bringing the swimmer to the surface where stroking could be resumed. Hence, little thought was given to potential propulsive benefits that may be obtained from the underwater kick phase following freestyle turning. As a consequence of the pursuit of performance excellence, two variations in underwater kicking styles are currently used in competitive freestyle swimming. These include traditional flutter kicking and prone or lateral dolphin kicking.

Underwater flutter kicking

Until recently, studies investigating flutter kicking in isolation (without arm stroking) were performed at the water surface. Alley (1952) explored active drag effects from a normal and reduced amplitude flutter kick, while Thrall (1960) examined the effect that the size and shape of the feet, kick frequency and kick amplitude have on the propulsive force of flutter kicking. The methodologies used in these investigations were detailed earlier in this review (see Chapter 2: Active drag studies). Findings from these studies indicate that larger amplitude flutter kicks produce greater free-kicking velocity and require a smaller towing force than reduced amplitude kicks. This was evidenced at velocities above and below maximal free-kicking speed (Alley, 1952; Thrall, 1960). Thrall (1960) used the addition of fins to increase the effective size of the feet and found a mean increase in mean free-kicking velocity and the effective propulsive force of the kick.

Fujiwara and Ogita (1997) investigated of the effect of foot frontal area and lower limb flexibility on maximal effort flutter kicking undertaken at the water surface. Their findings support those of Thrall (1960) in that foot frontal area was highly correlated with distance per stroke (kick) and swimming velocity (Fujiwara & Ogita, 1997). On the contrary, no relationships were found between knee angle and ankle extension with stroke rate, distance per stroke and kicking velocity. Fujiwara and Ogita (1997) concluded that during surface flutter kicking, larger foot frontal area would induce a higher propelling efficiency compared to increasing the flexibility of the lower limbs.

It is not known how applicable the findings from Alley (1952), Thrall (1960) and Fujiwara & Ogita (1997) are to underwater swimming. This is due, in part, to the hydrodynamic differences between surface and underwater swimming, and lack of studies examining underwater flutter kicking. As described earlier, Lyttle et al. (2000) examined the active drag experienced during underwater kicking from a variety of kicking techniques that included prone flutter kicking. All kicking trials were performed with maximal effort, although no limitation was placed on the amplitude or frequency of the kicks. A towing net force benefit (indicating that swimmers created less active drag when kicking than during streamline gliding) was shown during the prone flutter kicking at velocities up to 2.2 $m.s^{-1}$. This indicated that swimmers created less active drag when kicking than during streamline gliding at the same velocity. Despite not measuring maximal free-kicking velocities, 2.2 $m.s^{-1}$ appears in excess of the velocity any swimmer could achieve from underwater kicking only. Hence, this finding concurs with the earlier described surface kicking studies (Alley, 1952; Thrall, 1960) and indicates that positive benefits can be obtained when flutter kicking above maximal free-kicking velocities.

There is an obvious lack of published research in the area of underwater flutter kicking kinematics. Although it appears clear that kick frequency and amplitude affect surface kick velocity, their effect on underwater flutter kicking is not known. Therefore, closer examination of underwater flutter kicking kinematics is essential to determine optimal underwater kicking technique. This knowledge could then be applied to the kick phase following turns and lead to improved turn performance.

Underwater undulatory swimming (dolphin kicking)

Surprisingly, the introduction of underwater dolphin kicking to freestyle turns evolved from changes to backstroke starts and turn technique. This modification to backstroke swimming reached an extreme level at the Seoul Olympics in 1988 where significantly faster times resulted from the use of an underwater undulatory swimming (UUS) motion, prior to surfacing following the start and turns. Despite modification to the rules of swimming by FINA restricting the maximum underwater swimming distance following starts and turns to 15 m for all strokes, this distance is anecdotally considered adequate for swimmers to gain an advantage (Arellano et al., 2000). It is now widely known that UUS, also referred to in swimming as underwater dolphin kicking, enables many swimmers to maintain velocity equal to or greater than that of backstroke. Further, Vorontsov and Rumyantsev (2000) claim underwater kicking is, at the least, no slower than surface stroking, whereas UUS has been reported to possibly be the second fastest stroke to freestyle (Blanksby, 1999). Despite anecdotal evidence supporting the use of UUS following starts and turns, this area of human swimming has only recently gained attention from researchers.

Underwater undulatory swimming in aquatic animals

Pelagic fish research indicates that a transverse wave progressing along the body from head to tail is the most effective swimming movement, almost entirely regardless of shape or size (Wu, 1971). Consequently, numerous attempts have been made to determine the mechanisms of propulsion from this undulatory swimming technique. Any active swimming body propels itself by transferring momentum from their moving parts to the surrounding water, while the rate of transfer of momentum determines the amount of thrust generated (Ungerechts et al., 1998). When some fish perform undulatory swimming, water masses are set into rotation from the heaving and pitching of the body and caudal fin (fluke in dolphins). These rotating masses of water are known as vortices (Arellano et al., 2000; Ungerechts et al, 1998; Ungerechts et al., 1999). A schematic representation of vortex generation relative to a swimming dolphin is presented in Figure 2.6.

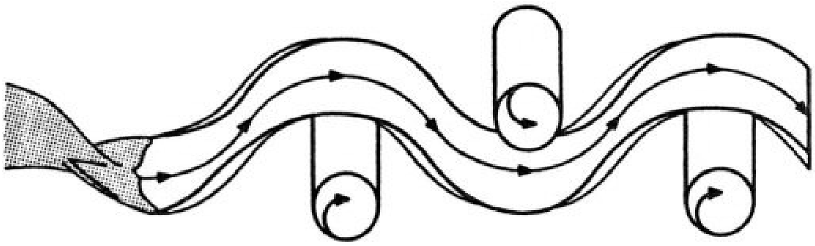

Figure 2.6. Wake of swimming dolphin with vortices (from Ungerechts et al., 1998, p. 4).

Numerous authors have described varying theories on the production of thrust from vortex generation (Arellano, 1999; Arellano et al., 2000; Colman et al., 1998; Colwin, 1984; Triantafyllou & Triantafyllou, 1995; Ungerechts et al, 1998; Ungerechts et al., 1999; Ungerechts, Persyn & Colman, 2000; Videler, 1993). Ostensibly, thrust is obtained by either cancelling out the vortex rotation at each fluke reversal point or by the creation of a propulsive jet from a combination of clockwise and counter clockwise vortices (Ungerechts et al., 1998).

Ungerechts et al. (1998) stated that the kinetic energy of a vortex is dependent on the mass of water and the square of the velocity of the rotating water. Hence, it can be postulated that larger and more rapid undulatory movements should produce greater transfer of energy into vortices and therefore, increased swimming velocity. Aspects of this theory have been investigated and supported in aquatic animal research. For example, fish species that swim with lateral undulations almost universally increase tail-beat frequency as swimming velocity increases (Jayne & Lauder, 1995). Similarly, dolphin swimming velocity increases with increased vertical tail-beat frequency (Ungerechts et al., 1998).

Various techniques have been used to examine the relationships between undulatory swimming and swimming velocity in certain aquatic animal species. Videler and Kamermans (1985) reported a dimensionless expression for velocity in terms of body lengths per tail beat period (L/T) and used this value for inter-specific comparison of swimming performance between species. They found that dolphins, which advance approximately 0.9 body lengths per tail-beat (L/T), swim with higher efficiency compared with the performance of other fish species (Mackerel, 0.8 L/T; Trout, 0.6 L/T; Eel, 0.55 L/T).

Similarly, a dimensionless Strouhal number that represents the ratio of unsteady and steady motion has been applied to UUS. The Strouhal number represents the time taken for a water particle to traverse the length of the body with respect to the time to complete one cycle, and is defined by the equation:

$$S = f\,L / u$$

Where S is the Strouhal number, f is the cycle frequency, L is the characteristic length and u is the velocity (Ungerechts et al., 1998).

Videler and Kamermans (1985) examined the differences between the up-stroke and down-stroke in slow swimming dolphins. It was found that the down-stroke generates more propulsive thrust than the up-stroke. The authors attributed this finding to increased drag on the body during the up-stroke. However, they postulated that thrust from the up- and down-strokes would become more balanced at higher velocity. Further, Videler and Kamermans (1985) found the up-stroke and down-stroke for dolphins swimming at slow velocity to be equal in duration. This finding was in contrast to earlier dolphin research that found the up-stroke to be performed more quickly than the down stroke (Purves, 1963, as cited in Ungerechts, 1983a; Ungerechts, 1983b). Comparison of findings between these investigations is limited, however, due to insufficient detail being presented in the published reports regarding swimming speed.

Ungerechts et al. (1998) noted that although dolphin swimming velocity increases with tail beat frequency, tail beat amplitude and frequency are independent. They reported dolphin tail beat amplitudes do not exceed greater than 25 % of total body length. Tests on other fish species indicate average specific amplitudes (kick amplitude/body length) represent values approximating 0.2 or 20 % (Hertel, 1966). This suggests optimal kick amplitudes exist for certain aquatic animals that swim with an undulatory motion.

Underwater undulatory swimming in humans

As for flutter kicking, studies investigating dolphin kicking in isolation (without arm stroking) were first performed at the water surface. Barthels and Adrian (1971) investigated slow and maximal surface dolphin kicking as performed by four university level swimmers using a combination of electrogoniometry and electromyography (EMG). Hip, knee and ankle flexion and extension patterns were recorded simultaneously with each of three pairs of lower extremity antagonistic muscles: rectus abdominis and lumbar erector spinae; rectus femoris and biceps femoris; and tibialis anterior and medial gastrocnemius. Although the analysis was confined to descriptive interpretation, the authors noted that greater joint amplitudes were synonymous with the increase in velocity from slow to sprint kicking. However, they noted kick frequency appeared to affect velocity more than hip, knee and ankle joint amplitudes. On the basis of muscle activity patterns recorded in the lower leg, Barthels and Adrian (1971) concluded that the development of greater ankle plantar flexion capacity appears to contribute more to increasing movement velocities while dolphin kicking than lower leg strength development.

Jensen and McIlwain (1979) modelled lower extremity forces during dolphin kicking from the performances of two international calibre swimmers. Joint moments of force were estimated from hip, knee and ankle displacement data that were obtained from film analysis of the dolphin kicking trials. Analyses were also confined to descriptive interpretation, while kick amplitude and frequency, velocity, and position relative to the surface (on or below) were not reported. Examination of the up-stroke and down-stroke joint moment curves indicated the existence of a co-ordinated timing pattern that followed a sequence from hip to knee to ankle (Jensen & McIlwain, 1979). Jensen and McIlwain (1979) concluded that reaction forces provide propulsion for the swimmer during the down-stroke, as evidenced by an increase in forward velocity, and resistance during the up-stroke.

The quantum of research published by biologists on the mechanics of fish motion is much greater than that reported on human swimming (Videler, 1993). Given that many aquatic animals display morphological and functional attributes that appear to refect the optimal design characteristics required for movement through water, it is believed that investigation of their form and movement may provide information to inform the development of strategies to improve the efficiency of human swimming (Lyttle, 1999; Ungerechts et al., 1998). Ungerechts (1983a, 1983b, 1985 & 1987) and Ungerechts et al. (1998) have led the way in applying aquatic animal movement mechanics to human swimming. During the early 1980s, Ungerechts (1983a) compared the undulatory movement patterns of the rear body parts of dolphins and dolphin kicking during butterfly swimming in humans. Human up-stroke and down-stroke dolphin kick amplitudes and the duration for the up- and down-strokes were found to be statistically similar. Conversely, the duration for the up-stroke in dolphins was significantly faster than the down-stroke. The faster up-stroke observed in dolphins was considered most likely due to the substantially greater muscle masses used in the up-stroke than those involved in the down-stroke. Furthermore, Ungerechts (1983a) postulated that a powerful down stroke might risk the uptake of air bubbles and prove less hydro-dynamically favourable.

The tail and lower leg movement frequencies were similar for both dolphins and humans (Ungerechts, 1983a). Despite this, the up-stroke of the dolphin fluke was performed significantly faster than the up-stroke of the swimmer's feet, at equal movement velocities (Ungerechts, 1983a). Notwithstanding anatomical differences, direct comparison of undulatory movements of the two species is compromised in this study because the up- and down-stroke durations in the human swimmers would invariably have been constrained by the timing and role of counterbalancing force generation of the butterfly arm stroke.

Following continued research on dolphin swimming, Ungerechts et al. (1998) presented a review paper, which applied the hydrodynamics of fish swimming to human swimming. The authors stated that despite obvious differences in body form, all fast swimming vertebrates prefer oscillation of the tail and the phase coupling of heaving and pitching of semi-lunate shaped flukes and suggest human swimmers should also adopt this motion during swimming (Ungerechts et al., 1998). Moreover, they support the use of undulatory motion principles and emphasised the need for increased swimmer flexibility, especially in the ankle. In addition, Ungerechts et al. (1998) noted a human swimmer has less ability to set water into rotation than dolphins (due to the shape of their feet and ankles). They suggested that human swimmers can increase the amount of water set into rotation by using a whip-like action to emphasize the reversal action of the kick thereby incorporating the principles associated with phase coupling of heaving and pitching. Specifically, increased ankle flexibility is thought to cause a larger phase shift between the motion of the shank and foot, which produces greater rotational momentum (Ungerechts, 1987).

There are relatively few investigations examining UUS in humans. Shimonagata, Taguchi and Taba (1997) investigated the wave motions during underwater dolphin kicking by seven skilled and two unskilled butterfly swimmers. Each subject performed underwater dolphin kicking at three subjective velocities (fast, medium and slow) during which, muscle activation (seven selected muscles) was recorded via EMG and video images were captured using underwater video (60 Hz). Shimonagata et al. (1997) reported swimming velocities ranging between 1.06 $m.s^{-1}$ to 1.65 $m.s^{-1}$ for the skilled swimmers and from 0.53 $m.s^{-1}$ to 0.70 $m.s^{-1}$ for the unskilled swimmers. However, the kicking depth was not specified. Based on previous drag research (Hertel, 1966; Lyttle et al., 1998) depth may have affected the resistive drag and subsequent swim velocities between trials and swimmers. Skilled swimmer hand-to-ankle phase analysis and muscle activation patterns demonstrated a harmonic wave action that moved across the entire length of the body. Conversely, the unskilled swimmers demonstrated a constrained motion and failed to transfer oscillations from hand to hip. No relationship between kick amplitude and velocity was reported.

One emerging area of study into human UUS has been developed in competitive fin-swimming (Baly, Favier, Durey & Berton, 2002; Colman et al., 1998; Gautier, Baly, Zanone & Waiter, 2004; Luk, Hong, Chu & Li, 1999; Tamura, Nakazawa, Sugiyama, Nomura & Torii, 2002; Zamparo, Prendergast, Termin & Minetti, 2002). Fin-swimming is a sport of speed usually practiced on or under the water surface, in which performance is based on whole-body oscillations while wearing a mono or pair of large fins (Gautier et al., 2004). Experienced human swimmers fitted with masks and fins have demonstrated a constant stride length (body lengths per tail beat) of 0.5 L/T, while swimming at various velocities underwater (Videler & Kamermans, 1985). Colman et al. (1998) analysed the movement of one international level swimmer performing sub-maximal UUS with and without fins. Estimation of the mass of water added to the swimmer's mass was determined using a dye visualisation system. Acceleration of the total body centre of mass (CM_{global}) was observed during the kick down-stroke and at the end of the kick up-stroke (Colman et al., 1998). The authors hypothesised that the even velocity of the CM_{global} could explain why flexible butterfly swimmers demonstrate faster swimming when kicking below the water surface than during the stroke. Research by Luk et al. (1999) also demonstrated peak horizontal velocity of the CM_{global} to coincide with maximum downward velocity of the fin during underwater undulatory fin-swimming. Notably, the different kick frequencies and amplitudes used in fin-swimming are likely to bear little application to UUS without fins due to the significant increase in surface area and the greater flexibility demonstrated by the dolphin-like fluke (fin).

Recently, Arellano et al. (2000) used a comparative approach to determine critical kinematic elements of UUS by examining the performance differences between different levels of swimmers. Nineteen (12 male, 7 female) internationally ranked senior and junior swimmers and 13 (7 male, 6 female) national age-group swimmers each performed two trials of maximal UUS, over a distance of 15 m. Data were obtained for more than 7.5 m from wall push-off to ensure the velocity of the body was obtained via swimming propulsion only. Trials were also performed at a depth of 0.5 m deep and no restriction was placed on the kick amplitude. Numerous kinematic measures were obtained via a 2D analysis of recorded underwater video images (50 Hz) to facilitate comparison between the groups.

For all swimmers, horizontal velocity of the CM was observed to increase during the down-stroke with maximal values occurring prior to completion of this movement phase (Arellano et al., 2000). This finding is in agreement with previous underwater undulatory fin-swimming (Colman et al., 1998; Luk et al., 1999) and animal UUS studies (Videler & Kamermans, 1985). With the exception of mean vertical velocity of the CM and kick amplitude, correlation analysis within the international level subject group demonstrated significant relationships between the mean velocity of the CM and all other velocity measures; kick horizontal displacement and the maximum knee flexion angle. This finding suggests kick amplitude is unrelated to UUS velocity and contrasts with the findings from surface dolphin (Barthels & Adrian, 1971) and fluter kicking studies (Alley, 1952; Thrall, 1960).

Comparative analysis between groups indicated that for a full kick cycle (one consecutive up- and down-stroke) the international level swimmers demonstrated significantly higher mean horizontal velocities for the centre of mass, hip and toe (Arellano et al., 2000). In addition, the international group performed with significantly higher kick frequency, maximal knee flexion, and kick amplitude per horizontal distance (amplitude/horizontal displacement of the kick). Kick amplitudes, however, were not significantly different between the groups despite the international group being taller. When normalised for height, Arellano et al. (2000) found the percentage of kick amplitude related to body heights were 34.31 % and 36.58 % for the international and national groups, respectively. This indicates that relative to their height, the national group kicked with larger amplitude while swimming significantly slower. This finding and the fact that dolphin tail beat amplitudes do not exceed 25 % of their body length (Ungerechts et al., 1998) suggest that optimal underwater kicking amplitudes may exist for human UUS.

Limitations of the study design used by Arellano et al. (2000) restrict the ability to utilise their data in the determination of optimal UUS technique. That is, the identification of critical technique characteristics is limited due to morphological and other likely differences between the subject groups. Consequently, performance comparison was likely to favour the taller (Larsen et al., 1981; Toussaint et al., 1990), older and most likely heavier and stronger international swimmers and therefore, not necessarily reflect a more ideal technique. For this reason, future UUS studies should examine relatively homogeneous subject populations.

More recently, Arellano, Pardillo & Gavilan (2003) investigated the usefulness of an adapted Strouhal number in evaluating human underwater undulatory swimming. The equation for the adapted Strouhal number is:

$$\mathrm{StN} = A_{p-p}\, f / U$$

Where StN is the Strouhal number, A_{p-p} is the tail-beat peak-to-peak amplitude (the distance from the peak of the tail fluke up-stroke to the peak of the down-stroke), f the stroke frequency (Hz) and U the swimming velocity (Fish & Rohr, 1999, as cited in Arellano et al., 2003).

Nineteen (12 male, 7 female) international and 13 (7 male, 6 female) national age-group swimmers were examined performing two 15 m maximal effort UUS sprints at a minimum depth of 1 m. The kinematic variables used in the analysis included the velocity of the CM and feet, kick frequency, amplitude and horizontal length, and calculated Strouhal numbers. All analysed variables showed significant differences ($p<0.01$) between both groups except for kick amplitude (Arellano et al., 2003). Arellano et al. (2003) reported better swimmers to have lower Strouhal numbers and significantly higher velocities of the CM, despite both groups using similar amplitude kicks. The lower Strouhal numbers observed for the better underwater undulatory swimmers is not unexpected given that performance improvement would result in an increase to the equation denominator (velocity), which in turn has a lowering effect on the Strouhal number. Hence, for this purpose, Strouhal numbers simply indicate UUS efficiency and do not provide insight into optimal UUS technique.

Most recently, Lyttle and Keys (2004) sought to discriminate between large amplitude, slow underwater dolphin kicking and small amplitude, fast underwater dolphin kicking using computational fluid dynamics (CFD). Data input into the CFD model was performed using kinematic information obtained from one elite male swimmer performing each of the two kicking patterns and from accurately mapping (3D) the swimmer's body shape using a Cyberware WBX whole body laser scanner. Pilot testing indicated the CFD model provides valid and reliable results that are in agreement with previous empirical testing of passive drag. Comprehensive results of the dynamic CFD modelling and comparisons are still to be published (Lyttle & Keys, 2004).

Flutter kicking vs. dolphin kicking

Despite a recent increase in research investigating freestyle turns and underwater kicking techniques, only one study was found in the literature that directly compared flutter and dolphin kicking kinematics (Sheeran, 1980). Sheeran (1980) examined the range of motion in the knee and ankle articulations of 14 male university level swimmers during performance of the front flutter, back flutter and dolphin kicking techniques. Waterproofed electrogoniometers were attached to the knee and ankle of each swimmer to measure the range, maximum flexion, maximum extension and the mean mid-point of the range. Other methodological details were not detailed fully and therefore it was not possible to determine factors such as the kicking velocity and kick position relative to the surface (on or under).

For the knee joint, dolphin kicking produced significantly ($p<0.05$) larger range and degree of maximum flexion than during flutter kicking (Sheeran, 1980). At the ankle, no significant difference was observed between the kick styles despite the dolphin kicking trials producing a considerably larger range (13 %), and greater flexion and extension maximums. Unfortunately, this investigation described the differences in joint kinematics only and therefore, conclusion cannot be drawn regarding the superior kicking technique with respect to velocity.

As discussed previously, Lyttle et al. (2000) compared the relative merits of underwater flutter and dolphin kicking during active towing. This investigation demonstrated that neither kick style had a significant advantage over the other, although there was a trend for the dolphin kick to consistently produce lower net towing forces (Lyttle et al., 2000). During this investigation participants were instructed to kick maximally without limitation placed on kick amplitude or frequency. As no kinematic analysis was applied to the individual kicking techniques used, the effect that variations in kick style have on net towing force remains unknown.

In conclusion, no study was found in the literatures that have directly compared the use of flutter and dolphin-kicking during freestyle turn performance. Moreover, comparative kicking studies reported to date are nominal and lack detailed kinematic analysis (Lyttle et al., 2000; Sheeran, 1980). Therefore, as a consequence of this shortfall, comparison of underwater flutter and dolphin kicking is one area in need of greater attention from researchers in order to empirically determine the superior underwater kick method.

Review summary

Performance in competitive swimming is measured by total race time and is made up of the sum of the times taken starting, stroking and turning. Therefore, gains or loses in either of these three race components can significantly affect a swimmer's performance. In the freestyle turn there are chances to improve performance through maximising wall contact and reducing drag throughout the push-off and glide phase (Lyttle & Benjanuvatra, 2004; Sanders & Byatt-Smith, 2003). In addition, minimising drag and optimising propulsion during the underwater kicking phase, prior to stroke resumption, could achieve performance improvements. However, a comparative lack of studies investigating underwater kicking techniques, specific to turn exits, means there is limited scientific evidence upon which underwater kick selection and technique can be based.

Methods of defining and subsequently quantifying turn performance were found to vary within the literature. Differences in the definition of the commencement and completion of the turn bring about this variation. Fixed arbitrary distances appear to be the preferred method for measuring turns as they provide an objective measure of turn performance, suitable for comparing variations in turning techniques. The set distances of 5 m in and 5 m out (5 m round trip time) have been used most commonly in recent investigations (Blanksby et al., 1998; Blanksby et al., 2004; Blanksby, Gathercole et al., 1996; Lyttle et al., 1999; Takahashi, Sakata et al., 1983). Despite a growing body of knowledge pertaining to this area of interest, the majority of freestyle turn investigations have focussed predominantly on total turn time comparisons and describing the kinetics of wall contact.

Various authors highlight the importance of optimal force applied to the wall during turns (Blanksby, Gathercole et al., 1996; Blanksby, Hodgkinson et al, 1996; Lyttle et al., 1999) and the need to reduce deleterious drag during the streamlined glide following push-off from the turn (Lyttle & Benjanuvatra, 2004; Sanders & Byatt-Smith, 2003). Specifically, higher push-off velocities from freestyle turns are achievable when combinations of low peak drag force; high peak propulsive force and an increased wall push-off time are optimised (Lyttle et al., 1999). However, empirical data of 3D forces in freestyle turns are lacking across all swimming proficiencies and warrant further investigation. Although it is apparent from the literature that several kinematic parameters play critical roles in turn performance, a comprehensive body of knowledge pertaining to turn kinematics is yet to be established. Therefore, further investigations examining turn kinematics are required to conclusively quantify critical elements of freestyle turn performance.

The effect of hydrodynamic factors upon swimming turn proficiency has received little attention from investigators despite the importance of streamlining during and after wall push-off. Although some conflict exists between findings, previous measurements of passive drag indicate that body position, glide depth and glide velocity affect the magnitude of the resistance (Benjanuvatra et al., 2002; Clarys & Jiskoot, 1975; di Prampero et al., 1974; Lyttle et al., 1998; Maiello et al., 1998). In particular, passive drag decreases with greater glide depth to 0.4 m deep, after which significant reduction in drag is not found (Lyttle et al., 1998). Active drag values measured during swimming have yielded inconsistent findings across investigations. Trends in the results suggest swimming technique plays a greater role in active drag than body form measures (Clarys, 1986; Kolmogorov & Duplishcheva, 1992, Kolmogorov et al., 1997; Toussaint, de Groot et al., 1988), although this concept remains equivocal. Few investigations are known to report the active drag created during kicking only. Consequently, findings are inconclusive and further examination of active drag during kicking is required.

The current body of scientific knowledge regarding optimal underwater kicking style and technique is insufficient to enable specific conclusions to be drawn. Subsequently, swimmers in elite competition currently use a large range of underwater turning strategies with very little scientific rationale applied in their selection (Lyttle & Keys, 2004). Research indicates that undulatory swimming is most efficient for certain species of aquatic animal (Wu, 1971) and that swimming velocity increases with increased tail beat frequency (Jayne & Lauder, 1995; Ungerechts et al., 1998). Furthermore, tests indicate that tail beat amplitudes do not exceed greater than 25 % of total body length for dolphins and kick amplitude/body length ratios average approximately 20 % in other fish species (Hertel, 1966). It is apparent from limited research conducted into swimming kicking that kick amplitude, kick frequency and ankle flexibility are related to kick velocity (Alley, 1952; Barthels & Adrian, 1971;

Thrall, 1960; Ungerechts et al., 1998). However, optimal kicking amplitudes and frequencies for underwater kicking are yet to be elucidated. In addition, the relationships between anthropometry and underwater kicking proficiency are not clear. Hence, there exists a need to examine and compare technique related kinematics between underwater swimming styles so that factors contributing to optimal underwater kicking may be elucidated. Moreover, a need exists to explore underwater flutter and dolphin kick kinematics at speeds representing those velocities experienced following wall push-off during turning.

By investigating the use of flutter and dolphin kicking following the turn and underwater kicking across a range of velocities, deficiencies in current knowledge will be addressed. Clearer understanding of the relative merit of each underwater kick style will therefore enable coaches and swimmers to select and refine turn wall-exit technique to improve freestyle turn times.

Chapter 3

Study 1: Traditional and Modified Freestyle Tumble Turns by Age-Group Swimmers

Modified manuscript of
"A comparison and analysis of traditional and modified freestyle tumble turns by age-group swimmers"
Journal of Human Movement Studies, 38(2), 93-108. (2000).

Introduction

Improved training methods, increased international competition and biomechanical improvements of strokes, starts and turns have all contributed to improved swimming performance over time. In addition, advances in equipment technology and facility design that have enhanced methods of measuring performance and improved the swimming environment have also contributed to improved swimming performances, respectively. Underwater force plates, windows for obtaining underwater video, wave reducing lane ropes and deck level pools of greater depth are examples of this. Furthermore, rule changes, such as the new backstroke turn where less distance is swum and decreased wave drag caused by the head submerging in breaststroke, have also caused reductions in swim times. One technique development is the modification of the freestyle tumble turn to incorporate underwater dolphin kicks after the start and following each turn in order to improve swimming performance.

Maglischo (1993) estimated that improving turns can decrease a sprint race time by at least 0.2 s per pool length and that greater improvements in race time could occur in longer races where more turns are involved. Despite their importance to overall swimming performance, there is limited research directed to swimming turns. Limited availability of underwater force platforms and technical difficulties associated with high speed film analysis, which gather kinetic and kinematic data in water respectively, are considered the major factors which have limited research in this area (Blanksby, Gathercole et al., 1996; Hay, 1988).

All swimming turns are comprised of the transfer from normal stroking during the wall approach (time-in), the time spent actually turning and the time from push-off to normal stroking resumption (time-out). Time-out can be minimised by increasing the impulse applied to the wall during push-off (Blanksby, Hodgkinson et al., 1996; Chow et al., 1984; Lyttle et al., 1999; Nicol & Kruger, 1979; Takahashi, Yoshida et al., 1983), and by minimising resistive drag during the glide (Maglischo, 1993). Blanksby, Gathercole et al. (1996) emphasised the need to maintain a streamlined position for an appropriate length of time to optimally utilise the velocity off the wall and ensure a smooth transition from the glide to the commencement of stroking. Blanksby, Gathercole et al. (1996) also stated that it was an advantage to have more extended lower limbs (greater tuck index), decreased wall contact time, high peak force on the wall and to optimise the push off glide in decreasing turn times.

Modifications have been made to the backstroke start and these were demonstrated to extreme at the Seoul Olympics in 1988 where a swimmer travelled most of the first length underwater and broke a world record. Significantly faster times were produced due to the utilisation of underwater dolphin kicking prior to surfacing and resuming backstroke swimming. Subsequent modifications to the rules of backstroke by FINA (Federation Internationale De Natation Amateur) have resulted in the distance that this technique may be performed underwater being reduced to 15 m. A similar change was made to freestyle starts and turns by FINA at a technical conference held on the 5th January 1998. This change stated that the head of the swimmer must break the surface of the water not more than 15 m after the start and each turn. Despite restrictions placed on the distance travelled underwater during freestyle, the use of underwater dolphin kicking following the turn is within the rules of the stroke.

The concept underlying the modification of the freestyle turn by dolphin kicking underwater is to increase propulsion without undue resistance in the period between rapid acceleration from the push-off the wall and the subsequent ‘break out’ into the stroke resumption. With turning comprising a large proportion of some freestyle races, the potential time gain from modifications to the turn can be appreciable. Research to date has not verified whether freestyle tumble turns which incorporate underwater dolphin kicks off the wall improve turn performance over that achieved from the traditional freestyle turns in which flutter kicking is used. Despite many swimmers using underwater dolphin kicking when exiting the wall in freestyle races, the use of underwater dolphin kicking as a superior method of exiting from the turn is yet to be empirically demonstrated. Hence, the purpose of this study was to compare the biomechanical and performance characteristics of a modified freestyle tumble turn which used a dolphin kick off the wall with the traditional freestyle turn that incorporates a flutter kick off the wall, in age-group swimmers.

Methodology

Sample

This study used male and female age group competitors from the UniSwim club at the University of Western Australia. The group comprised 20 males of mean height (±SD), 152.9 ± 10.5 cm; mass, 43.05 ± 8.9 kg; and age, 11.2 ± 1.3 yrs; and 17 females of mean height, 154.4 ± 9.09 cm; mass, 41.9 ± 7.8 kg; and age, 11.4 ± 1.3 yrs. The subjects who volunteered regularly participated in swimming training for three sessions, each of 1.5 hours duration, per week. The mean 50 m short course freestyle swim time for this group was recorded to be 40.69 ± 3.62 s.

Data Collection

Approval from the University of Ballarat and the University of Western Australia Human Research Ethics Committees and informed consent from all participants was obtained prior to commencement of the investigation. The warm up preceding the 50 m swim test trials consisted of a 200 m freestyle swim followed by 3 x 50m freestyle swims. In addition, two to three practice turns were carried out on the force plate to ensure familiarity. Data were collected from groups of eight swimmers with each swimmer performing 4 x 50 m maximal freestyle efforts from a push start on a 6-min departure interval in a 25 m pool. Subjects were randomly assigned which turn type to attempt (flutter kick or dolphin kick) for their first two test trials and then completed the remaining two test trials with the alternate variation. Practise trials were deliberately excluded from the warm-up to obtain performance data relative to each swimmer's current ability at each turn type. The test trial 50 m swim times were hand timed and video images of all subjects were recorded and stored for analysis. Absolute peak forces (XYZ) and wall contact times (WCT) were calculated from data obtained via an underwater force plate.

Supplementary 25 m flutter kick and dolphin kick time trial tests were administered to 22 of the 37 participating subjects. These subjects performed one dolphin kick and one flutter kick time trial at maximum velocity on their front, arms fully extended while holding a kickboard with the chin remaining at water level. Kick order was randomly assigned and hand held stopwatches were used to record the 25 m times. This was carried out to investigate whether swimmers were more proficient at dolphin or flutter kicking.

Instrumentation

A Kistler (Type 9253A11) waterproof force plate (600 mm length x 400 mm width x 140 mm thick), was mounted vertically at the pool end to measure the forces (X = horizontal, Y = vertical, Z = perpendicular to the wall) generated by the swimmers on the wall. The plate was positioned in the centre of the lane at water level and reached below the surface to a depth of 600 mm. Force was sampled at 200 Hz and the signals were sent via an 8 channel Kistler amplifier (Type 9861A) and stored for analysis via an AP30 software system (Pearce, 1996).

A National Panasonic M4 S-VHS video camera was fitted with a Vivitar 0.42x ultra wide-angle lens and positioned in a viewing window 10.5 m lateral to the swimmer's approach to the wall and 5 m distant from the turning end of the pool. An exposure time of 1000.s^{-1} was used with the camera set to record at 25 frames.s^{-1} with the images viewed at 50 fields.s^{-1}. All video images were passed through a For.A VTG-33 video timer where digital numbering was imprinted before being recorded on a

Panasonic VCR (model AG-7350-E). A 10 m horizontal scaling device was marked in 100 mm sections and positioned 800 mm below the surface of the water. The device extended from the leading edge of the force plate to the 10 m mark (see Figure 3.1). The 10 m scale reference allowed the position of the subject image to be referenced to the position of the scale in the same area as the image, thus negating possible image distortions from use of a wide angle lens.

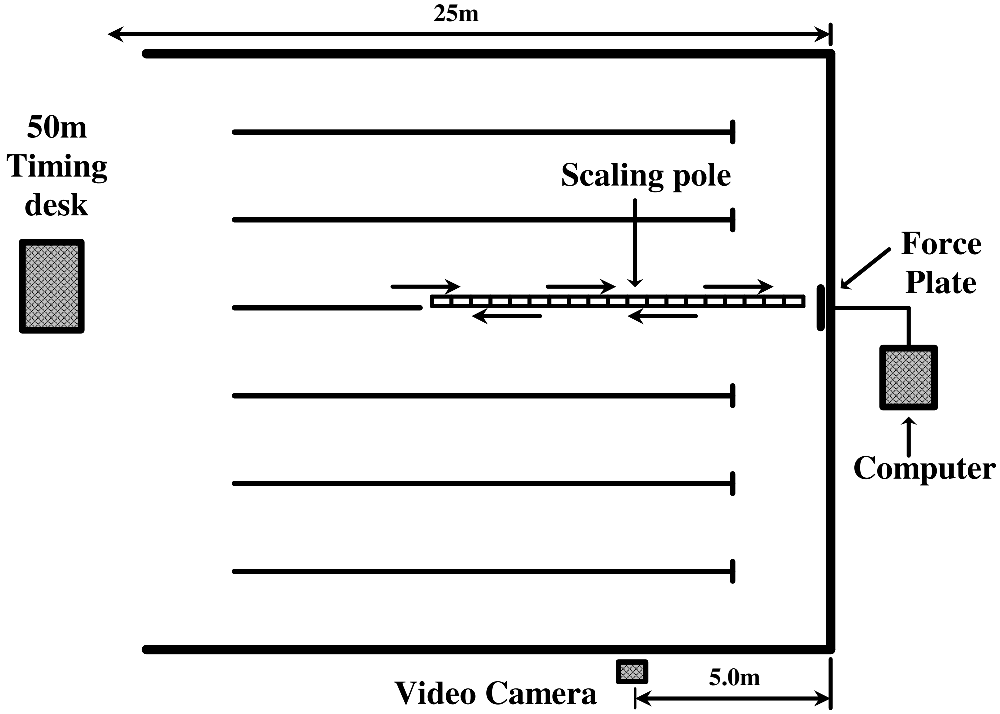

Figure 3.1. Schema for equipment set-up.

Data analysis

This study compared two turn techniques (dolphin and flutter) using 5 m RTT as the criterion performance measure. Both turn techniques incorporated a considerable portion of swimming which is independent of the technique used. To compare the two turn techniques, it was also deemed necessary to examine for variation in the turning events preceding the initiation of kicking. The turn measures preceding the kicking phase which may have varied include: average swim velocity in, WCT, peak force in the X, Y and Z directions, wall exit velocity and kicking resumption distance, velocity and time. These measures were therefore recorded for comparison between the two turn techniques.

Wall contact analysis involved the calculation of absolute peak forces (N) in the X, Y and Z directions, and WCT (s). Determination of foot contact with the plate was made in accordance with the method adopted by Lyttle and Mason (1997). That is, foot contact was deemed to occur with sharp increases in X and Y directional forces. Peak force was the highest level recorded after the feet had contacted the plate while WCT was measured from first contact to departure of the feet from the plate. Despite some studies (Blanksby, Hodgkinson et al., 1996; Chow et al., 1984; Takahashi, Yoshida et al., 1983) showing increasing the impulse applied to the wall can reduce time out from the wall; impulse was not used in the present study.

The impulse produced by a swimmer on the wall can be developed in two different ways; high force with larger contact time or lower force with smaller contact time. The contribution of force and time are often masked within the resultant impulse. For example, some high jumpers have demonstrated decreased time of contact with the ground at take-off while still producing greater impulse (Bobbert, Mackay, Schinkelshoek & Huijing, 1986). Importantly, Blanksby, Gathercole et al. (1996) reported that swimmers with faster round trip times (RTTs) demonstrated significantly higher peak forces and decreased WCTs. Subsequently, peak force and WCT were considered appropriate measures of wall contact.

Blanksby et al. (1998) reported an inability to eliminate a bow wave effect being recorded by the underwater force plate during the breaststroke turn. There is likely to be similar contamination of the force readings obtained in the current study, due to a bow wave effect during a freestyle tumble turn. It is should be noted however, that it is likely that the bow wave effect generated during a freestyle turn is not quite the same as that generated during breaststroke and butterfly. The significance of this bow wave effect in the present study is considered minimal due to the relative nature of comparison within each subject's performance.

A scaled grid on the video monitor screen, constructed from the image of the 10 m underwater reference structure, enabled the calculation of distance using the vertex of the swimmers head as a reference. Average swim velocity was calculated while swimmers travelled between the 10 m and 5 m markers on the way in to the wall. The 5 m RTTs were calculated from the time taken for the vertex of the head to pass the 5 m mark on the way in and out from the wall. Wall exit velocity, leg and arm resumption distances (initiation of kicking and arm stroking, respectively), leg and arm resumption velocities and times and the distance and time until the head surfaced were calculated from the underwater video. All velocities were determined over a displacement of 30 cm prior to the commencement of wall exit, leg and arm resumption occurring. The resumption of kicking was defined as the first foot movement to break from a streamlined position while the resumption of arm stroking was defined as the first downward motion of the hand. The cessation of dolphin kicking was defined as the moment the feet began to separate into flutter kick.

Statistical analyses

The trial recording the fastest 5 m RTT while performing a tumble turn and flutter kick exit was chosen as the criterion turn to determine whether any gender differences existed. This was examined via an analysis of variance (ANOVA). The supplementary 25 m flutter kick and dolphin kick time trial scores were compared using a paired sample t-test. Further statistical analyses comprised a comparison of the swims that produced the fastest 5 m RTTs for the dolphin kick and flutter kick trials, within each subject. Summary statistics (mean, SD) for all variables were calculated for the entire data set. A paired-sample t-test was applied separately on each variable between the two turn techniques across each subject. The difference between the scores obtained from each subject's two performances was calculated by subtracting the flutter kick trial results from the dolphin kick trial results.

Group Means (±SD) of the fastest 33 % and the slowest 33 % dolphin kick turn trials using the 5 m RTT as the criterion measure were computed for all performance measures and the mean difference recorded. Finally, an ANOVA was carried out on the averages of the fastest 33 % versus the slowest 33 % dolphin kick turn trials using all measures. This was performed in an attempt to identify those measures that contribute to faster dolphin kick turns.

Digitising a single trial 10 times was also performed to determine digitiser consistency. Alpha correlation coefficients were used to compare the recorded trip time at each of the four set distance marks (10, 7.5, 5, 2.5 m), in and out from the wall. In addition, separate alpha correlation coefficient analyses were performed on each of the grouped distance, time and velocity measures. Results from the reliability analyses indicated all standardised alpha coefficients to be greater than 0.995 (refer Appendix E). Therefore, high digitiser consistency was demonstrated. The statistical analysis package SPSS (version 10.0.5, 1999) was used for all statistical data analyses.

Results

An ANOVA revealed no significant differences ($p>0.05$) for the flutter kick 5 m RTT between the 20 males and 17 females. Consequently, all subjects were pooled into one group with a sample size of 37. Comparison of the supplementary 25 m flutter kick and dolphin kick time trial scores using a paired sample t-test was performed to determine the dolphin kicking ability of the group compared to flutter kicking. Results from the supplementary 25 m kicking time trials revealed significant differences ($p<0.05$) between the dolphin kick (mean 30.68 ± 4.07 s) and flutter kick (mean 26.73 ± 2.60 s) times, suggesting that subjects in the present study were less proficient at performing 25 m kickboard assisted dolphin kicking than flutter kicking.

Examination of means for each subject's dolphin and flutter kick turn trial scores indicated significant differences ($p<0.05$) in 6 of the 15 performance measures (see Table 3.1). For the dolphin kick, these measures were; slower 5 m RTT, greater arm resumption distance and time, slower arm resumption velocity, greater surface distance and time than during the flutter kick trials.

An ANOVA performed on the measures of the fastest 33 % and the slowest 33 % dolphin kick turns indicated significant differences ($p<0.05$) between the groups in 8 of the 18 performance measures (see Table 3.2). For the fastest 33 %, these measures were: faster 5 m RTT and average swim velocity, greater peak Z force, faster wall exit, kick resumption and arm resumption velocities, smaller arm resumption time and shorter time spent dolphin kicking. However, no significant differences were found between WCT, peak X and Y force, kick resumption distance and time, arm resumption distance, surface distance and time, the number of dolphin kicks and the distance travelled dolphin kicking.

Table 3.1. Comparison of Means (± SD) for age-group swimmer variables (n=37).

	Dolphin kick (n=37)	**Flutter kick (n=37)**	**Difference (n=37)**
5m RTT (s)	8.53 ± 0.90	8.10 ± 0.67	0.42*
Ave. swim velocity in ($m.s^{-1}$)	1.19 ± 0.11	1.21 ± 0.09	-0.03
WCT (s)	0.67 ± 0.21	0.62 ± 0.19	0.06
Peak force Z (N)	564.64 ± 166.68	553.13 ± 148.85	11.51
Peak force Y (N)	52.98 ± 27.63	52.52 ± 28.16	0.46
Peak force X (N)	39.33 ± 14.52	40.67 ± 14.39	-1.34
Wall exit velocity ($m.s^{-1}$)	1.84 ± 0.24	1.86 ± 0.28	-0.02
Leg resumption distance (m)	2.36 ± 0.40	2.17 ± 0.30	0.20
Leg resumption velocity ($m.s^{-1}$)	1.38 ± 0.28	1.47 ± 0.27	-0.09
Leg resumption time (s)	0.48 ± 0.21	0.40 ± 0.22	0.08
Arm resumption distance (m)	3.64 ± 0.63	2.76 ± 0.61	0.88*
Arm resumption velocity ($m.s^{-1}$)	1.04 ± 0.25	1.26 ± 0.25	-0.22*
Arm resumption time (s)	1.69 ± 0.63	0.86 ± 0.52	0.83*
Surface distance (m)	3.66 ± 0.75	2.92 ± 0.67	0.74*
Surface time (s)	1.66 ± 0.72	0.98 ± 0.53	0.68*
Number of dolphin kicks	2.46 ± 1.07		
Dolphin kick distance (m)	1.57 ± 0.67		
Dolphin kick time (s)	1.46 ± 0.60		

* Denotes significant difference ($p<0.05$) using paired t-test.

Table 3.2. Comparison of group means (± SD) of the fastest 33 % dolphin kick turn trials and the slowest 33 % dolphin kick turn trials using 5 m RTT as the dependent variable.

	Fastest 33 %	**Slowest 33 %**	**Difference**
5m RTT (s)	7.59 ± 0.48	9.50 ± 0.59	-1.90*
Ave. swim velocity in ($m.s^{-1}$)	1.29 ± 0.10	1.10 ± 0.58	0.19*
WCT (s)	0.56 ± 0.18	0.72 ± 0.21	-0.16
Peak force Z (N)	695.83 ± 148.39	443.75 ± 55.71	252.08*
Peak force Y (N)	62.97 ± 34.33	43.74 ± 20.54	19.25
Peak force X (N)	44.54 ± 11.62	41.51 ± 17.20	3.03
Wall exit velocity ($m.s^{-1}$)	1.95 ±0.25	1.70 ± 0.16	0.25*
Leg resumption distance (m)	2.44 ± 0.41	2.28 ± 0.46	0.16
Leg resumption velocity ($m.s^{-1}$)	1.47 ± 0.24	1.17 ± 0.25	0.30*
Leg resumption time (s)	0.44 ± 0.22	0.53 ± 0.27	-0.09
Arm resumption distance (m)	3.77 ± 0.59	3.67 ± 0.74	0.10
Arm resumption velocity ($m.s^{-1}$)	1.21 ± 0.19	0.85 ± 0.14	0.35*
Arm resumption time (s)	1.53 ± 0.42	2.06 ± 0.75	-0.54*
Surface distance (m)	3.95 ± 0.66	3.56 ± 0.85	0.39
Surface time (s)	1.65 ± 0.56	1.82 ± 0.93	-0.17
Number of dolphin kicks	2.42 ± 0.90	2.58 ± 0.99	-0.17
Dolphin kick distance (m)	1.59 ± 0.52	1.69 ± 0.67	-0.10
Dolphin kick time (s)	1.29 ± 0.42	1.79 ± 0.63	-0.50*

* Denotes significant difference ($p<0.05$) using an ANOVA.

Discussion

The supplementary 25 m flutter kick and dolphin kick time trial tests were administered to examine the participants' proficiency at dolphin kicking compared with flutter kicking. Significant differences ($p<0.05$) were observed between the dolphin kick (mean 30.68 ± 4.07 s) and flutter kick (mean 26.73 ± 2.60 s) 25 m times. The mean difference of 3.95 s indicates that subjects in the present study were slower at performing the dolphin kick technique and are therefore less likely to perform well at a freestyle tumble turn using dolphin kicks off the wall. However, the validity of this test is considered questionable in that the use of kick boards may have over restricted the movements required for good underwater kicking and therefore misrepresented underwater kicking proficiency.

Little difference in average swim velocity between the dolphin kick and flutter kick turn trials indicated that subjects were swimming equally on approach to the turn. Similarly, little difference in WCT was observed between the dolphin kick and flutter kick turn trials (mean dolphin trial WCT = 0.06s longer). Consequently, WCT prior to dolphin kicking push-off did not affect peak force in the Z, Y and X directions when compared with their flutter kick turns. The mean peak Z force for the dolphin and flutter kick turns were 553.13 N and 564.64 N, respectively. No significant difference in the peak Z force between the techniques was shown. These peak Z force values are slightly lower than those reported by Blanksby, Gathercole et al. (1996) who reported mean peak Z force values of 693.35 N in their investigation of turning forces by age-group swimmers. Younger, shorter and lighter subjects used in the present study are a likely explanation for this variance.

The mean peak forces in X and Y for the dolphin kick trials (40.67 N and 52.52 N) showed no significant difference from those recorded during the flutter kick trials (39.33 N and 52.98 N). These figures represent approximately 5 to 10 % of peak Z force, indicating the majority of wall contact force was directed correctly to affect the change in horizontal direction. Despite the absolute values of peak force being used in the analysis, preliminary investigation with regard to force direction, indicated very little difference in the raw values of peak Y force between the dolphin and flutter kick trials. This indicated greater upwards force was not produced during the push-off in an attempt to obtain greater depth for dolphin kicking.

In the present study, mean WCTs for the dolphin and flutter kick trials (0.62 s and 0.67 s, respectively) were slightly greater than those reported by Blanksby, Gathercole et al. (1996) (0.58 s). The difference in WCT between studies reflects the slight variation in swimmer population. No difference observed in peak force and WCT between the dolphin kick and flutter kick turn techniques caused no difference in velocity after push-off between the two techniques. The resumption of kicking took place 0.20 m further from the wall during the dolphin kick trials. The velocity at which this occurred was 0.09 $m.s^{-1}$ less than the flutter trials and occurred 0.08 s later. None of these differences were significant which further supports the notion that the two techniques did not significantly differ from the approach to the wall, during the turn and push-off, and to the resumption of kicking.

Recent turning studies have used the 5 m RTT and the criterion measure for turn performance (Blanksby et al., 1998; Blanksby, Gathercole et al., 1996; Blanksby, Hodgkinson et al., 1996). By doing so, only the features that contribute directly to the turn are measured. Results in the present study reveal the subjects performing the dolphin kick turn had significantly slower 5 m RTTs compared with the traditional flutter kick turn. Subjects performing the dolphin trial recorded a mean time that was 0.42 s slower for the 5 m RTT. Only 9 of the 37 subjects recorded faster dolphin kick trial 5 m RTTs. A likely explanation for the slower dolphin mean times is the significantly ($p<0.05$) slower arm resumption velocity (0.22 $m.s^{-1}$) exhibited during the dolphin trial. This slower velocity at arm resumption was also combined with a significantly ($p<0.05$) greater arm resumption distance (0.88 m) and time (0.83 s). Therefore, during the dolphin trials, the swimmers travelled significantly further and for a longer time before commencing to stroke and their mean velocity was significantly

($p<0.05$) slower than their flutter kick trial. Only eight of the 37 subjects resumed stroking during the dolphin trials at a velocity equal to or greater than their average swim velocity. This compares with 18 of the 37 subjects resuming stroking during the flutter trials at or above their average swim velocity, highlighting the need for these swimmers to refine this section of the race.

Whilst dolphin kicking, it was observed that most subjects were fully submerged but did not execute the transition from dolphin kicking to arm stroking optimally. Surfacing prior to completion of dolphin kicking or commencing arm stroking prior to surfacing was evident among some swimmers. A lack of experience and skill at performing the dolphin turn technique is a probable cause. Consequently, the decreased horizontal velocity will increase 5 m RTT. The use of competent age-group but not high calibre swimmers was chosen to provide a wider variety of performance scores. It was hoped that this would enable clearer identification of areas contributing to good performance. Unfortunately, the unexpected superior flutter kicking ability and the inability of these swimmers to adapt quickly and with skill to the dolphin kick turn strategy limited the study. That is, swimmers performed better at what they were most familiar with: flutter-kicking turns. In addition, dolphin kicking for use during turns could be a difficult skill to learn and might be slowed because of confusion between underwater dolphin kicking and the dolphin kicking used in butterfly stroking. The failure of dolphin kicking to impress is evidence that the analogy of swimmers to marine dolphins is incorrect. Nonetheless, the wide differential of results also highlights basic skill deficiencies, which require coach attention and that it cannot be automatically assumed that the dolphin technique will be a superior swim style for this population.

The average distance travelled prior to surfacing (0.74 m) and the time taken to surface (0.68 s) also were significantly greater for dolphin kicking than in the flutter kick trials. This extra distance and time was not unexpected if numerous dolphin kicks are employed by the swimmer. As indicated, the arm resumption velocity for the dolphin kick trials was 0.15 m.s^{-1} slower than the average swim velocity. Velocity at arm resumption for the flutter kick trials occurred at a velocity slightly above (0.05 m.s^{-1}faster) the average swim velocity. It is considered essential for optimal performances that arm stroking is resumed when horizontal velocity is near that of average swim velocity following a turn (Blanksby, Gathercole et al., 1996). Therefore, these swimmers judged the arm resumption velocity quite successfully. The resumption of stroking during the dolphin trials occurred at a slower velocity than for average swimming and therefore contributed to the increased 5 m RTT. These swimmers spent excessive time dolphin kicking underwater before stroke resumption. Skill at self-selection of the optimal moment at which to resume swimming is important. Perhaps greater familiarity with the dolphin kick task would be addressed by means of a training study.

Comparison of the differences between the fastest 33 % and slowest 33 % dolphin kick turn trials indicated a significant 5 m RTT difference of 1.90 s between the groups. The fastest 33 % recorded a mean WCT of 0.16 s less than the slowest 33 % as well as a significantly greater mean peak Z force (252.08 N) during push-off. Blanksby et al. (1998) studied the turning technique of 23 age group breaststrokers. They reported that 5 m RTTs decreased when peak forces off the wall were increased. Several studies have also reported a relationship between shorter WCT, higher peak Z force and decreased RTT (Blanksby, Gathercole et al., 1996; Blanksby, Hodgkinson et al., 1996; Takahashi, Yoshida et al., 1983). The combination of longer WCT and lower peak Z force at push-off exhibited by the slowest 33 % dolphin kick turn trials in the present study has contributed to the slower mean wall exit velocity (0.25 $m.s^{-1}$) and 5 m RTT (1.9 s) for this group.

Despite the wall exit velocity and the resumption of kicking occurring at significantly slower horizontal velocities between the fastest and slowest 33 % groups (0.25 $m.s^{-1}$ and 0.30 $m.s^{-1}$, respectively), the differences in the distance travelled dolphin kicking (0.10 m) and the number of dolphin kicks (0.17) between the two groups were similar. That is, both groups travelled the same distance using the same number of dolphin kicks. However, the time-spent dolphin kicking varied significantly ($p<0.05$) between the groups (0.5 s). Hence, the fastest 33 % performed their dolphin kicks with an average velocity of 1.23 $m.s^{-1}$ compared to 0.94 $m.s^{-1}$ recorded by the slowest 33 %. These results equate to kick frequencies of 1.88 $kicks.s^{-1}$ and 1.44 $kicks.s^{-1}$ for the fastest and slowest 33 % groups, respectively. This result indicates that the swimmers who recorded the faster dolphin kick turns possess the ability to dolphin kick at a faster rate and produce greater propulsion. Reasons why some swimmers are able to perform more efficient dolphin kicking were not investigated in the present study. Further investigation into this concept is warranted.

Conclusion

The significantly faster flutter than dolphin kick 25 m kick times indicated that this sample of age-group swimmers possessed superior ability at this kicking technique. No difference existed between dolphin and flutter kicking turns for the approach to the wall, during wall contact and push-off, and to the resumption of kicking. Therefore, and not surprisingly, results showed the traditional flutter kick method of exiting from the freestyle turn to be significantly faster than turns with a dolphin kick exit. The observed difference in turn performances was therefore most likely due to the swimmers possessing more mature flutter kicking movement patterns, rather than the effectiveness of a given kicking strategy. That is, performances were best in what they were most familiar. Despite this and the dolphin kick turn technique being performed by the subjects for the first time during the warm up and trials, 9 of 37 subjects recorded faster dolphin kicking RTTs. This indicates that the use of dolphin kick turns may be an individually suited skill and necessitates further investigation by means of a training study. The large range of dolphin performance variability demonstrated in the use of age-group swimmers also indicates that future research be directed towards a more homogeneous group of swimmers with higher skill. Consideration of these ideas will assist in endorsing the adoption of a modified dolphin kick turn as a means of improving swim performance.

Chapter 4

Study 2: Practice and Performance of a Modified Freestyle Tumble Turn by Age-Group Swimmers.

Introduction

Swimming turns are an integral part of a swimmer's performance (Beckett, 1985; Newble, 1982) and often determine who will win an event (Adler, 1979; Carpinter, 1968; Chow et al., 1984; Thayer & Hay, 1984; Ward, 1976). Despite a lack of documented research into swimming turns (Hay, 1988; Blanksby, Gathercole et al., 1996), greater attention has recently been focussed on this aspect of swim performance (Blanksby et al., 1998; Blanksby et al., 2004; Blanksby, Gathercole et al., 1996; Blanksby, Hodgkinson et al., 1996; Daniel et al., 2002; Hodgkinson & Blanksby, 1995; Lyttle et al., 1999; Lyttle & Mason, 1997). Underwater force plates and videography have been two developments that have facilitated greater interest in the investigation of swimming turns (Blanksby, Hodgkinson et al., 1996; Nicol & Kruger, 1979; Takahashi, Yoshida et al., 1983).

Recent swim turn investigations have used 5 m round trip time (RTT) as the criterion turn performance measure (Blanksby et al., 1998; Blanksby et al., 2004 Blanksby, Gathercole et al., 1996; Blanksby, Hodgkinson et al., 1996;). This distance is considered to adequately represent the three main phases of a turn: the approach, the tumble turn and wall contact, and the exit from the turn. Key elements of the traditional tumble turn technique that decrease turn times have been identified as more extended lower limbs (greater tuck index), decreased wall contact times, high peak forces on the wall and an optimised push-off glide (Blanksby, Gathercole et al., 1996). These authors also emphasised the need to maintain a streamlined position for an appropriate length of time to optimally utilise the speed off the wall and ensure a smooth transition from the glide to the commencement of stroking.

Coaches and swimmers constantly strive to enhance performance by modifying or developing swimming techniques. One technique modification to freestyle swimming is to incorporate underwater dolphin kicks after the start and following each turn. The use of underwater dolphin kicks following the dive start and each turn during freestyle races is a performance technique that is now used by many swimmers. However, validation of this technique as a superior method of exiting from the turn remains to be shown. Further, the key elements of this turn technique are yet to be identified. To endorse the use of the modified turn technique, individuals should be trained in this turn technique style before a legitimate comparison can be made between the effectiveness of the two techniques. Hence, the purpose of this study was to examine and compare the biomechanical and performance characteristics of a modified freestyle tumble turn and the more traditional freestyle tumble turn before and after six weeks of dolphin kick and dolphin kick turn practice.

Methods

Sample

Subjects volunteered from a sample of convenient age-group competitors from the Uniswim club at The University of Western Australia (Mean ± SD 50 m short course freestyle time 40.34 ± 3.18 s). The group comprised nine males of mean height (±SD) 150.64 ± 10.37 cm; mass, 41.25 ± 8.08 kg; and age, 11.02 ± 1.19 yrs; and 13 females of mean height, 155.28 ± 9.29 cm; mass, 40.57 ± 7.15 kg; and age, 11.69 ± 1.29 yrs. The subjects were enrolled to participate in swimming training for three sessions per week, each of 1.5 hours duration.

Data collection

Approvals from the University of Ballarat and the University of Western Australia Human Research Ethics Committees and informed consents from all participants were obtained prior to commencement of the trials. The 50 m swim test trials were conducted in accordance with the procedures described in Chapter 3. Participants completed 4 x 50 m maximal swim efforts (two with dolphin turn, two with flutter turn) before undertaking dolphin kick turn training and following six weeks of dolphin kick turn training.

The six-week training period included specific dolphin kick and dolphin kick turn practice. During this time, subjects were given 5 - 10 min per training session to learn, practise and refine their skill at dolphin kicking and dolphin kick turns. Attendance at a maximum of 18 training sessions, three per week, was possible throughout the intervention period. Practices were conducted during each regular training session warm-up, and included instruction and feedback from coaches.

Participants were instructed to practice dolphin kicking underwater with the arms extended and one hand placed on the other in a streamlined position. The head was to be placed between the upper arms and instructions were given to squeeze the arms against the ears. The kick was to be performed with "loose" ankles while generating a wave like action with the legs, beginning from the hips. Forceful flexion and extension of the knees was required with the legs remaining together and synchronised at all times. Specific instructions regarding the speed and size of kicks were not given with swimmers encouraged to adopt their own natural kick technique they felt produced their fastest underwater kick velocity. Participants were required to perform between two and five dolphin kicks using the technique explained above, following wall push off and prior to the resumption of stroking. Feedback was given to reinforce correct or incorrect performance technique during the practice trials. Subject attendance was recorded over the six-week training period.

Instrumentation

The instrumentation used in the present investigation was identical to that described in Chapter 3.

Data analysis

This study also compared dolphin and flutter kicking turn techniques using 5 m RTT as the criterion performance measure. The methods of raw data collection treatment used in Chapter 3 were also used to treat data in the present investigation. In addition, turning events preceding the initiation of kicking were measured and treated as covariates to control for pre-kick variation between techniques. The turn measures preceding the kicking phase which may have varied include: average swim velocity in, WCT, peak force in the X, Y and Z directions, wall exit velocity and kicking resumption distance, velocity and time. High digitiser reliability (alpha correlation coefficients > 0.995) was demonstrated for this method of analysis in the preceding chapter and was assumed to persist in this investigation.

Statistical analyses

Each subject's fastest 5 m RTT for the dolphin kick and flutter kick turn trials were chosen for analysis. Summary statistics (mean, SD) for all pre- and post-test dolphin kick and flutter kick turn variables, and the difference between each kick variable measure, were calculated. Performance differences due to gender were examined by comparing each swimmer's fastest 5 m RTT (pre-test trial) for both a turn and flutter kick exit. This was examined via an independent t-test (alpha level $p<0.05$).

Preliminary analysis involved comparing dolphin kick and flutter kick 5 m RTTs using multivariate-repeated measures ANOVA. Kick type and time (pre- and post) were entered as fixed factors with type III sums of squares and an alpha level of $p<0.05$. Due to the small sample, all performance trials (dolphin, flutter, pre- and post-training) were combined into a sample of $n=88$ cases. This larger sample facilitated identification of the contribution of performance variables occurring before the resumption of kicking. This approach was deemed necessary to enable greater statistical power to be achieved.

A Pearson product-moment correlation co-efficient matrix was constructed to identify the relationships between the variables preceding the resumption of kicking and

5 m RTT. A multiple stepwise regression analysis was then conducted using 5 m RTT as the criterion measure. Selected performance variables measured before to the resumption of kicking were used in this analysis to identify their contribution to 5 m RTT.

A univariate repeated measures ANOVA, using those variables found to contribute to 5 m RTT as covariates, was conducted to determine whether dolphin kick turns improved by comparison with flutter kick turns following six weeks of dolphin kick and turn training. Kick type and time were entered as fixed factors while subject was treated as a random factor. Type I sums of squares and an alpha level of $p<0.05$ were used. Bonferroni pairwise comparisons were conducted to adjust the observed significance level for the fact that multiple comparisons were made (SPSS, 1999). All data were analysed using an SPSS Statistical Analysis Package (version 10.0.5, 1999).

Results

An independent t-test revealed no significant gender difference ($p<0.05$) for the flutter kick 5 m RTT before the experimental condition. Consequently, all subjects were pooled to form a sample size of 22. Summary statistics (mean, SD) for all pre- and post-test dolphin kick and flutter kick turn variables, and the differences between each kick variable measure, are presented in Table 4.1. The mean number of training sessions attended during the training period was 7.86 ± 3.24 (minimum 2, maximum 12) out of a possible 18. Excluding those participants with low attendance from the analysis was considered, however, the effect this would have had on the statistical degrees of freedom was deemed to be more limiting than the effect of retaining them.

A significant multivariate difference (p=0.04) existed between the dolphin kick and flutter kick turn types. No significant difference (p=0.066) was observed between the pre- and post-test results for 5 m RTT. The interaction between kick type and time was also non-significant (p=0.320), indicating that dolphin kick turns did not improve significantly more than flutter kick turns following dolphin kick and dolphin kick turn training. The Mauchly test of sphericity for kick type, test time and the interaction between kick type and time were all found to be non-significant. Therefore, the assumption of sphericity for these data was not violated. This result supported the decision to further explore the data in univariate form (n=88) with the inclusion of selected covariates.

Significant negative correlations were found between 5 m RTT and average swim velocity-in, peak force Z and Y, wall exit velocity and leg resumption velocity. Significant positive correlations were found between the 5 m RTT and WCT and leg resumption time (see Table 4.2). No significant correlations existed between the 5 m RTT and peak force X and leg resumption distance.

A multiple stepwise regression analysis was conducted to determine performance variables measured during the turn and prior to the resumption of kicking that best predict 5 m RTT. Due to the high degree of multi co-linearity shown between average swim velocity-in and 5 m RTT (r = -0.859), and because average swim velocity-in was measured prior to the start of measurement of RTT, average swim velocity-in was omitted from the regression analysis. Measures were added to the model when a variable was determined to add predicability to the regression equation at an alpha level of p<0.05. The results of the stepwise regression for 5 m RTT are presented in Table 4.3. The best pre-kick predictors for 5 m RTT in order of importance were: peak force

Z, wall exit velocity, leg resumption velocity and WCT. These variables were found to account for 46% of the variance in 5 m RTT. A lack of patterning and the appearance of normality in the residual plots supported the decision to pool all performance trials into a sample of $n = 88$.

The univariate repeated measures ANOVA indicated significant ($p<0.05$) effects in all four covariates. The adjusted marginal means for 5 m RTT by kick type (dolphin and flutter) and test time (pre- and post) are plotted in Figure 4.1. When statistically controlling for the covariates, a significant difference ($p=0.02$) was observed between the dolphin kick and flutter kick turn types for 5 m RTT. Similarly, a significant difference ($p=0.02$) was observed in 5 m RTT over time. The interaction between kick type and time was found to be non-significant. This indicated that the dolphin kick turns did not improve significantly more than flutter kick turns following dolphin kick turn training.

Table 4.1. Pre- and post-test dolphin kick and flutter kick means (± SD) for age-group swimmers (n=22).

	Pre-test			**Post-test**		
Variable	**Dolphin kick**	**Flutter kick**	**Difference**	**Dolphin kick**	**Flutter kick**	**Difference**
5 m RTT (s)	8.34 ± 0.80	8.09 ± 0.60	0.25	8.11 ± 0.74	7.96 ± 0.78	0.15
Average swim velocity in ($m.s^{-1}$)	1.20 ± 0.12	1.20 ± 0.09	0	1.23 ± 0.11	1.24 ± 0.12	-0.01
WCT (s)	0.62 ± 0.18	0.55 ± 0.18	0.06	0.56 ± 0.17	0.58 ± 0.18	-0.02
Peak force Z (N)	558.05 ± 156.84	561.75 ± 167.88	-3.70	551.86 ± 145.89	549.00 ± 136.52	2.85
Peak force Y (N)	59.41 ± 31.24	56.26 ± 34.69	3.15	48.96 ± 24.07	53.40 ± 27.18	-4.44
Peak force X (N)	43.62 ± 16.15	41.61 ± 13.44	2.01	45.83 ± 20.23	41.71 ± 14.22	4.12
Wall exit velocity ($m.s^{-1}$)	1.82 ± 0.26	1.82 ± 0.29	0	1.86 ± 0.24	1.89 ± 0.27	-0.03
Leg resumption distance (m)	2.30 ± 0.44	2.13 ± 0.30	0.17	2.39 ± 0.32	2.28 ± 0.30	0.11
Leg resumption velocity ($m.s^{-1}$)	1.39 ± 0.28	1.53 ± 0.29	-0.14	1.36 ± 0.28	1.51 ± 0.28	-0.15
Leg resumption time (s)	0.45 ± 0.19	0.39 ± 0.25	0.07	0.45 ± 0.15	0.40 ± 0.22	0.06
Arm resumption distance (m)	3.51 ± 0.63	2.73 ± 0.46	0.78	3.66 ± 0.67	3.22 ± 0.37	0.44
Arm resumption velocity ($m.s^{-1}$)	1.11 ± 0.22	1.29 0.26	-0.18	1.12 ± 0.16	1.12 ± 0.19	0.00
Arm resumption time (s)	1.55 ± 0.58	0.81 ± 0.32	0.73	1.61 ± 0.53	1.15 ± 0.33	0.46
Surface distance (m)	3.57 ± 0.72	2.91 ± 0.67	0.66	3.77 ± 0.75	3.29 ± 0.46	0.48
Surface time (s)	1.55 ± 0.64	0.97 ± 0.47	0.57	1.71 ± 0.58	1.25 ± 0.34	0.46
Number of dolphin kicks	2.45 ± 1.06			2.27 ± 0.63		
Dolphin kick distance (m)	1.56 ± 0.71			1.40 ± 0.45		
Dolphin kick time (s)	1.37 ± 0.57			1.28 ± 0.46		
Training sessions				7.86 ± 3.24		

Table 4.2. Pearson product-moment correlations for all variables preceding the resumption of kicking and 5 m RTT.

	5 m RTT	**Av. swim vel. in**	**WCT**	**Peak force Z**	**Peak force Y**	**Peak force X**	**Wall exit vel.**	**Leg R dis.**	**Leg R vel.**	**Leg R time**
5 m RTT (s)	1	-.859*	.237*	-.554*	-.321*	-.127	-.503*	-.150	-.404*	.232*
Average swim velocity in (m.s^{-1})		1	-.026	.458*	.196	.123	.551*	.229*	.281*	-.131
WCT (s)			1	-.186	-.080	-.161	.082	.119	-.027	.100
Peak force Z (N)				1	.261*	.292*	.435*	.255*	.239*	-.073
Peak force Y (N)					1	.182	.309*	.424*	-.008	.278*
Peak force X (N)						1	.211*	.084	-.033	-.028
Wall exit velocity (m.s^{-1})							1	.408*	.251*	.083
Leg resumption distance (m)								1	-.265*	.812*
Leg resumption velocity (m.s^{-1})									1	-.420*
Leg resumption time (s)										1

Note. Vel. = velocity; Dis. = distance; R = resumption

* Denotes significance ($p<0.05$)

Table 4.3. Stepwise regression equation and results for prediction of 5 m RTT

Variable	Regression coefficient	Beta weight	R squared	Adjusted R-squared
Peak force Z	-1.6E-03	-0.321	0.307	0.299
Wall exit vel.	-0.898	-0.319	0.392	0.378
Leg resumption vel.	-0.661	-0.242	0.447	0.427
WCT	0.822	0.197	0.483	0.458

Constant: 11.138

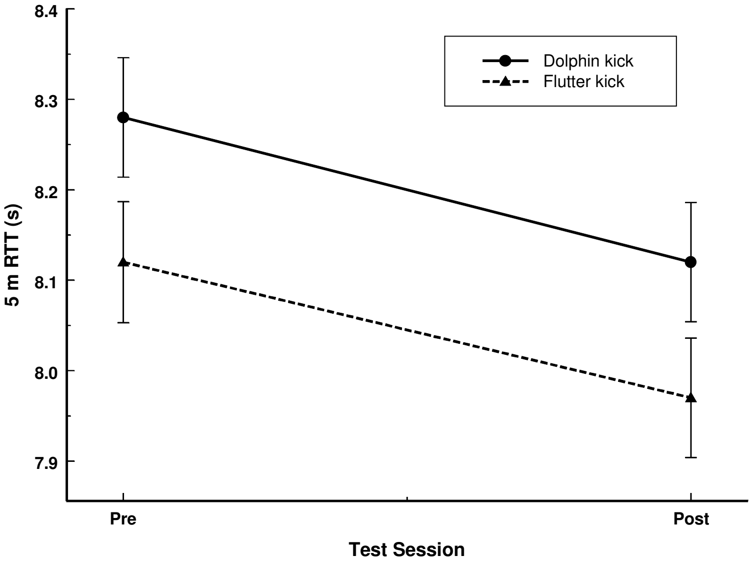

Figure 4.1. Plot of adjusted 5 m RTT means for kick type and test time

Discussion

This study examined the use of a modified freestyle tumble turn which involved a dolphin kick off the wall (dolphin kick turn) compared to the traditional freestyle tumble turn (flutter kick turn), before and after six weeks of dolphin kick and dolphin kick turn practice. The relatively small sample size and the poor attendance level at training throughout the six-week intervention period affected the interpretations of the present study. Subsequently, the present findings are limited to the sample population.

Participants in the present study recorded approximately 20 % lower horizontal peak forces (555 N) during the turn than those reported by Blanksby, Gathercole et al. (1996) for age group swimmers (693 N). A difference in mean age between participants of the two studies (current study, 11.41 ± 1.28 yrs, Blanksby, Gathercole et al., 1996, 13 yrs ± 9 months), and the subsequent differences in mass and strength, are considered likely reasons for the difference in horizontal peak force. The effect of age on wall horizontal peak force has been illustrated in turning studies with older, more experienced swimmers by Lyttle et al. (1999) and Takahashi et al. (1982) who reported considerably higher horizontal peak forces, ranging from 1189 N (Lyttle et al., 1999) to 1711 N (Takahashi et al, 1982).

Previous research indicates that reductions in passive drag during the glide phase following a turn could be achieved by gliding at a depth greater than 0.4 m (Lyttle et al., 1998). The absolute values of mean peak Y force did not indicate that subjects pushed off the wall with a greater upward force in an attempt to obtain greater depth for dolphin kicking than for flutter kicking. Mean peak Y and X forces during push-off were shown to represent approximately 5 to 10 % of the mean peak Z force. Therefore, it appears the majority of wall contact force was directed appropriately to effect the required change in horizontal direction.

Nicol and Kruger (1979) examined the horizontal impulse exerted during a push off the wall following tumble and open freestyle turns. Comparison of impulse relative to the push-off and tumble turns showed no significant differences. This finding allowed

Nicol and Kruger (1979) to associate differences between gliding length following the turn with greater resistance immediately after leaving the wall. Measurement of wall turning forces in the present study indicated similar (non-significant) horizontal peak forces between the dolphin kick and flutter kick turns at both the pre- and post-test times (range: 549 - 561 N). Similarly, differences in peak Y forces (range: 49 - 59 N) and peak X forces (range: 41 - 45 N) measured during the turn were minimal (non-significant) between the pre- and post dolphin kick and flutter kick turns. This result allowed a similar assumption to that of Nicol and Kruger (1979) to be made. That is, any observed difference in RTT between the two turn techniques may be associated with events other than wall contact forces.

The present study demonstrated WCTs ranging from 0.56 to 0.62 s. While similar to those shown by Blanksby, Gathercole et al. (1996), the present results are substantially longer than those reported in previous studies (Lyttle & Mason, 1997; Nicol & Kruger, 1979; Takahashi, Yoshida et al., 1983). Lyttle et al. (1999) stated that although a high WCT may not directly affect the final push-off velocity, it could negatively affect overall turn speed. Therefore, it is considered that the poorer turn performances demonstrated by age group swimmers could partly be attributed to the greater duration of the WCT.

Ostensibly, the modified dolphin kick turn and the more traditional flutter kick turn should not vary until the point where kicking is resumed. Despite little difference observed in wall force and WCT between technique trials, consideration for any differences in WCT and wall force between the dolphin and flutter kick turns was critical to allow differences in performance to be attributed only to technique type. Consequently, an adjustment for variation in performance prior to the resumption of kicking was necessary for valid statistical comparison between the two turn exit techniques. Regression of those performance variables measured before the resumption of kicking with 5 m RTT and using those variables shown to be highly predictive as covariates in further analysis achieved this.

Horizontal peak force was the best single predictor (r = -0.554) of 5 m RTT, and accounted for 30 % of the variance. Blanksby, Gathercole et al. (1996) also reported horizontal peak force as the best predictor of 5 m RTT for freestyle tumble turns by age-group swimmers. Similarly, Lyttle et al. (1999) found that higher peak force during push off results in higher instantaneous acceleration that, in turn, results in higher push off velocity. However, this was thought to only apply if drag force is not increased simultaneously. The present findings demonstrate a significant relationship between wall exit velocity and 5 m RTT. Therefore, it may be deduced that high horizontal peak force resulting in high wall exit velocity will ultimately result in lower RTTs.

The second-ranked predictive factor was wall exit velocity (r = -0.503; Adjusted R^2 = 38 %). A significant negative correlation indicated that greater the wall exit velocity would result in faster 5 m RTT. Differences in the definition and method used to calculate wall exit/push-off velocity limits the comparison of this result with previous research. However, attempts to increase wall exit velocity should not be at the expense of increasing the drag experienced by the swimmer (Lyttle et al., 1999).

Leg resumption velocity was the third-ranked predictive factor (r = -0.404; Adjusted R^2 = 42 %). This indicated that resuming the kick sooner and therefore at higher velocity resulted in faster 5 m RTT. Lyttle et al. (2000) concluded that initiating the kick too early in the glide would result in an increase in active drag and prematurely slow the swimmer. Conversely, gliding too long before kicking would adversely decelerate the swimmer, requiring energy to be used accelerating back to free swimming velocity. For reasons unexplained by the present data, subjects consistently delayed the resumption of kicking when performing the dolphin kick trials. The optimal selection of the moment to resume kicking following the turn would appear to be critical to maximising turn performance.

The fourth and final predictive factor included in the regression equation was WCT (r = 0.237; Adjusted R^2 = 46 %). This significant positive correlation indicated that decreased WCT resulted in faster 5 m RTT as found by Blanksby, Gathercole et al. (1996) and Blanksby, Hodgkinson et al. (1996). These findings suggest lowering WCT will contribute to a lower RTT. However, insufficient time to develop an optimum impulse will reduce the potential to increase wall exit velocity (Lyttle et al., 1999) and subsequently lead to an increase in RTT.

Lyttle et al. (1999) proposed that an optimal combination of low peak drag force, high peak propulsive force and sufficient wall push-off time were critical elements for achieving high push-off velocity following the turn. The present study identified high horizontal peak force, high wall exit velocity, high leg resumption velocity and low WCT as significant contributors to faster 5 m RTT. These findings suggest that those swimmers who optimise these factors during a turning motion will maximise performance by producing faster 5 m RTTs. Due to the significant impact these measures can have on 5 m RTT turn performance, it was deemed necessary to adjust for any pre-kick differences that may have existed between the dolphin and flutter kick trial performances. For that reason, the measures of horizontal peak force, wall exit velocity, leg resumption velocity and WCT were included as covariates in a univariate repeated measures ANOVA, to compare 5 m RTTs for the two kicking techniques.

Univariate analysis revealed a significant difference (p=0.02) between the dolphin kick and flutter kick turns for 5 m RTT. This indicated that the dolphin kick method of exiting the wall following a tumble turn is not as good as flutter kick for this population. Significant difference (p=0.02) in 5 m RTTs between the pre- and post-test trials, irrespective of turn type, suggested that overall turn performance improved following six weeks of dolphin kick and dolphin kick turn training. This result was not surprising considering the potential for rapid improvements in performance that can be noted in age-group competitors.

The statistically adjusted 5 m RTT means for pre- and post-test dolphin kick trials showed improved performance over time. This supports the notion that training, specific to the dolphin kick turn task, would improve dolphin kick turns. A similar reduction in the adjusted 5 m RTT means for the pre- and post-test flutter kick trials also occurred. No significant interaction (p=0.475) between kick type and time was observed. Therefore, dolphin kick turns did not improve significantly more when compared with flutter kick turns following six weeks of dolphin kick turn training. Hence, the improvements made in the dolphin kick turns were similar to those improvements made in the flutter kick turns.

Dolphin kick rates in the present study were 1.79 kick.s^{-1} and 1.77 kicks.s^{-1} for the pre-test and post-test trials, respectively. In addition, participants travelled 0.16 m less and spent 0.09 s less time dolphin kicking during the post-test trials, while recording faster 5 m RTT. While dolphin kicking might not be best for freestyle swimming turns, the improvements demonstrated in this investigation should benefit butterfly, medley, and most probably backstroke events.

Despite the present results supporting flutter kick as the superior method of exiting the turn, 8 of the 22 subjects recorded faster dolphin kick 5 m RTTs during the pre-test trials. Likewise, 8 of the 22 subjects recorded faster dolphin kick trial 5 m RTTs than flutter kick trials during the post-test trials. Of these, only four subjects recorded faster dolphin kick than flutter kick 5 m RTTs at both the pre-test and post-test trials. This result highlights the intrinsic variation that can be observed in the performances of age-group swimmers and that the efficient use of dolphin kick turns may be a technique only suited to certain swimmers. Further research involving larger sample sizes and a greater range of swimming ability is needed to allow conclusions to be made regarding the greater swimming population. The variations in amounts of training experienced by the subjects could have inflated the error terms in the statistical analyses. Future studies should attempt to ensure that subjects receive the same full-training experience for true-effects to be revealed.

Conclusions

On the basis of the results, and within the limitations of this study, it was shown that significant and equal improvements occurred in dolphin kick and flutter kick 5 m RTTs following six weeks of dolphin kick and dolphin kick turn practice. Therefore, the introduction of minimal turning practice for age-group swimmers is likely to result in significant reductions in turning times and should be noted by coaches and swimmers alike. Despite specific dolphin kick turn training; the flutter kick technique remained the superior method of exiting the wall, based on 5 m RTT, following a freestyle tumble turn for this population. Determination of the best underwater kick method to use following a turn appears unlikely with this age swimming population due to the presence of underdeveloped turning skill levels. Future turn exit research that intends to determine critical elements of performance should therefore be conducted on swimmers with mature movement patterns and greater ability to consistently reproduce performances.

Chapter 5

Study 3: Traditional and Modified Freestyle Tumble Turns by Skilled Swimmers

Modified manuscript of
"Traditional and modified exits following tumble turns by skilled swimmers". *South African Journal for Research in Sport, Physical Education and Recreation, 22*(1), 41-55. (2000).

Introduction

The importance of turns in swimming events is becoming increasingly evident. During some events, turning can comprise over a third of the total event time and is often a factor in determining final placing's (Huellhorst et al., 1988). Despite swimming turns being an integral part of competitive performance (Beckett, 1985; Newble, 1982) and influencing who will win an event (Adler, 1979; Carpinter, 1968; Ward, 1976), attention to this aspect of swim performance has only re-emerged in recent years.

Early research by Fox et al. (1963) focussed on comparing the time taken to perform different turn techniques. They found the energy expenditure between the open and closed turn (tumble turn) was similar but that the tumble turn was significantly faster. Studies have also investigated whether modifications such as 'piked' versus 'tuck' turns (Ward, 1976), and a double arm pull off the wall turn (Adler, 1979; Beckett,

1985) were faster methods of performing the tumble turn. Nicol and Kruger (1979) compared the swimming speeds and impulses generated by the freestyle flip turn and the open turn. No significant differences were evident between the two techniques for return swimming velocity, impulse and duration of impulse. However, complete turn time for the freestyle flip turn was significantly shorter than those of the open turn and resulted from differences in wall approach swimming times.

The availability of underwater force plates has lead to the collection of kinematic and kinetic data that affect turn performance (Blanksby, Gathercole et al., 1996; Chow et al., 1984; Huellhorst et al., 1988; Lyttle & Mason, 1997). Takahashi et al. (1983) investigated the propulsive forces generated by swimmers during a flip turn and during a push-off the wall and glide. Analysis of the force profiles revealed no significant differences in peak force and duration of push-off between the two conditions. Total impulse was, however, significantly higher for the flip turn (Takahashi et al., 1983).

Lyttle and Mason (1997) highlighted the difficulty in comparing turn studies due to differences in the operational definitions of when the turn commenced and finished. Hay and Guimaraes (1983) and Chow et al. (1984) defined turn commencement as the last hand entry before the wall (distance-in) to the end of the first stroke taken after the turn (distance-out). Fixed arbitrary distances of 3 m in to 6.5 m out (Thayer & Hay, 1984), 7.5 m in to 7.5 m out (Newble, 1982) and 5 m in to 5 m out (Blanksby, Gathercole et al., 1996) have also been used. Despite these differences, key elements of the current freestyle tumble turn have been identified. Time out can be minimised by increasing the impulse applied to the wall during push-off (Blanksby, Gathercole et al., 1996; Blanksby, Hodgkinson et al., 1996; Chow et al., 1984; Takahashi et al., 1983). Blanksby, Gathercole et al. (1996) also stated that it was an advantage to have more extended lower limbs (greater tuck index), decreased wall contact time (WCT), high peak force on the wall to optimise the push-off and glide in decreasing turn times.

Previous turn research has attributed decreases in round trip time (RTT) to improvements in those measures occurring prior to and during wall contact (Blanksby, Gathercole et al., 1996; Blanksby, Hodgkinson et al., 1996; Chow et al., 1984; Takahashi et al., 1983). While the importance of having more extended lower limbs (greater tuck index), decreased WCT and high peak force on the wall with decreasing turn RTT is recognised, the technique events occurring during ‘time out’ from the turn have been neglected and warrant investigation. Isolating the events following wall push-off allows the importance of the glide, the timing and duration of underwater kicking and the timing of stroke resumption in decreasing turn times to be quantified. Specifically, the effect of using different kicking techniques following wall push-off could be examined.

Arellano et al. (1996) developed a system for automatic timing of the swimming start. Trials using this system and the start performances of nine male (mean age 16.2 years) swimmers with more than five years competitive experience were conducted. Swim start performance was measured from the block to a distance of 10 m using four different conditions; start and glide without propulsion, start and freestyle kicking, start and butterfly kicking and start and freestyle swimming. Results showed superior water time (WT, the time from the instant of hand entry to 10 m) and total start time (ST, the time from the starting signal to 10 m) for the start and butterfly kicking trials (mean WT = 3.774 s, mean ST = 4.997 s) than the start and flutter kicking trials (mean WT = 3.924 s, mean ST = 5.131 s).

The findings of Arellano et al. (1996) highlight the need to further evaluate the use of undulatory movements during the underwater or swimming phases of the competitive strokes that occur during starts and turns. Despite many swimmers currently employing dolphin kicks during the exit phase of the turn during freestyle races, evidence regarding whether this technique modification is a superior method of exiting from the turn is not available. The findings of investigations in Chapters 3 and 4 demonstrated that flutter kick exits from the wall contribute to significantly lower 5 m freestyle turn RTTs in age-group swimmers. This was evidenced both before and after specific dolphin kick training. However, the large performance variation exhibited by these swimmers was considered a limitation with respect to accurate comparison of the two wall exit techniques. Hence, a replication of study one using more highly skilled swimmers was proposed. Therefore, the purpose of this study was to compare the biomechanical and performance characteristics of modified (dolphin kick exit) and traditional (flutter kick exit) freestyle tumble turns using swimmers of higher calibre than those measured in Chapters 3 and 4, respectively.

Methodology

Sample

Participants in the present study were members of the Swimming Victoria Junior Development Squad who attended a training camp at the University of Ballarat Aquatics Laboratory. Entry to the squad is based on swimmers having placed in the top 10 at the National Age Championships during that year. The group comprised eight males of mean height, 178.9 ± 7.03 cm; mass, 70.8 ± 6.59 kg; and age, 16.88 ± 2.42 years; and five females of mean height 169.5 ± 3.30 cm; mass, 61.0 ± 5.56 kg; and age 15.0 ± 1.22 years.

Data collection

Approval from the University of Ballarat Human Research Ethics Committee and informed consent from all participants was obtained prior to commencement of the trials. Data collection took place at the School of Human Movement and Sport Sciences Aquatics Laboratory, University of Ballarat, Australia. The warm up consisted of a 200 m freestyle swim and 3 x 50m freestyle swims. Two to three practice turns were carried out on the force plate to ensure familiarity with the test protocol. As this investigation comprised a replication of the study reported in Chapter 3 using swimmers of higher calibre, 50 m swim trial data were collected using similar procedures.

The swim trial that produced the fastest 5 m RTT for the dolphin kick and flutter kick turn techniques was chosen for analysis in this investigation. Despite using this measure to select better overall turn performances, the 5 m RTT as a criterion for comparing wall exit performance is potentially limiting. That is, a 5 m RTT incorporates a considerable portion of swimming and other turning manoeuvres that can vary in addition to variation due to using different wall exit strategies. Consequently, when isolating different kicking techniques used following the turn, variations over 5 m RTT could mask any differences that could occur as a result of the kicking phase. However, the investigations using age-group swimmers in Chapters 3 and 4 indicated that using different kicks during the out-phase of the turn do not affect time-in, WCT and other initial conditions prior to kick resumption when exiting the wall. Hence, the time taken from kick resumption to the 5 m mark following the turn represents an ideal criterion to compare the two turn techniques. Nonetheless, selection of the same time and velocity to resume kicking during both technique trials was considered unlikely to occur. Therefore, 5 m out-time, or the time it takes a swimmer to travel from last foot contact on the wall to the 5 m mark following the turn, was considered to represent a more precise criterion to examine whether there was an advantage in using dolphin or flutter kicking following the turn.

Chapters 3 and 4 indicated that variation in dolphin and flutter-kicking turns only occurred following kick resumption. With skilled swimmers, variation between dolphin and flutter kicking turn techniques was also expected to be evident following kick resumption only. However, turning performance measures prior to the resumption of kicking were measured again to ensure that the same findings apply to this group of skilled swimmers and that differences in the two turning styles were isolated to turn kicking technique. Those turning measures that may vary prior to kick resumption included; average swim velocity-in, WCT, peak force in the X, Y and Z directions, wall exit velocity and kicking resumption distance, velocity and time. When these events took place, with regards to turning time, were also considered important and subsequently examined for differences between the turn techniques. The performance measures recorded following the resumption of kicking (i.e. post-kick measures) included; arm resumption distance, velocity and time, and surface distance and time. The number of dolphin kicks, the distance travelled and the time spent kicking, were also recorded.

Instrumentation

The same model and settings reported in Chapter 3 for the underwater force plate, video camera and VCR were used for the collection of data in the present investigation. An identical 10 m scaling device was also used. The methods of raw data treatment used in the previous work were also used to treat data in the present investigation. The exception to this was the exclusion of 5 m RTT and the inclusion of a measure representing 5 m out-time. No reliability analyses were performed due to the use of similar analysis procedures and the high digitiser consistency demonstrated in Chapter 3.

Statistical analyses

A paired sample t-test was conducted to compare the two 50 m freestyle swim times for the trials using flutter kick wall exits to examine consistency of performance. Summary statistics (mean, SD) for the dolphin kick and flutter kick turn variables were calculated. Flutter kick trial results were subtracted from the dolphin kick trial results to obtain the difference between the mean scores for each turn measure.

Preliminary analyses, via a series of paired sample t-tests, were conducted to examine whether the performance measures recorded prior to the resumption of kicking varied significantly for the dolphin and flutter kick trials. Similar analyses were performed on those measures recorded following the resumption of kicking between the dolphin and flutter trials.

To further clarify the degree of similarity or variation between the two wall exit kicking techniques it was important to examine the degree of cumulative difference up to the point of the turn when kicking was resumed. A Pearson product-moment correlation coefficient matrix was constructed to identify the relationships between the variables preceding the resumption of kicking and 5 m out-time. A multiple stepwise regression analysis was then conducted using the 5 m out-time as the dependent variable. The performance variables measured before the resumption of kicking were used in this analysis to identify the contribution of these variables to 5 m out-time. Those performance variables found to contribute significantly to 5 m out-time where then used as covariates to account for any variation in performance that may have existed prior to the resumption of kicking.

A repeated measures ANOVA, using those variables found to contribute to 5 m out-time as covariates, was conducted to determine whether a significant difference existed between the dolphin kick and flutter kick 5 m out-times. Kick type was entered as a fixed factor while subject was treated as a random factor. Type I sums of squares were used for this procedure while an alpha level of $p<0.05$ was used for all statistical analyses. Bonferroni pairwise comparisons were conducted to adjust the observed significance level for the fact that multiple comparisons were made (SPSS, 1999).

Results

No significant difference ($p>0.05$) between each swimmer's first and second 50 m freestyle swim times (28.59 ± 1.65 s and 28.62 ± 1.73 s, respectively) for the trials using flutter kick wall exits. Summary statistics (mean, SD) for all pre- and post-dolphin kick and flutter kick turn variables, and the differences between each kick variable measure are presented in Table 5.1.

Examinations of the scores for each subject's dolphin and flutter kick turn trial performances revealed no significant differences in the pre-kick measures recorded up to and including push-off (see Table 5.1). These measures were: average swim velocity-in, WCT, peak Z, Y and X force and wall exit velocity. Therefore, the measures recorded prior to and including push-off during the turn were similar for the two techniques. Also, no significant differences were observed for leg kick resumption distance and time, between the two techniques. However, kick resumption velocity was significantly slower (p=0.03) for the dolphin kick turn trials. Thus, no statistical difference was observed between the two techniques for all performance variables measured prior to and at kick resumption except for kick resumption velocity, which was 0.17 $m.s^{-1}$ slower during the dolphin kick trials.

Table 5.1. Comparison of means (± SD) for swimmer variables (n=13).

		Dolphin kick (n=13)	**Flutter kick (n=13)**	**Difference (n=13)**
Pre-kick measures	Ave. swim velocity in ($m.s^{-1}$)	1.65 ± 0.10	1.62 ± 0.12	0.03
	WCT (s)	0.44 ± 0.12	0.49 ± 0.13	-0.05
	Peak force Z (N)	892.15 ± 246.82	864.82 ± 252.95	27.33
	Peak force Y (N)	120.95 ± 42.18	110.69 ± 44.52	10.26
	Peak force X (N)	75.72 ± 39.79	60.57 ± 20.39	15.15
	Wall exit velocity ($m.s^{-1}$)	2.58 ± 0.37	2.57 ± 0.33	0.01
	Leg resumption distance (m)	2.77 ± 0.19	2.70 ± 0.27	0.07
	Leg resumption velocity ($m.s^{-1}$)	1.90 ± 0.23	2.07 ± 0.26	-0.17*
	Leg resumption time (s)	0.44 ± 0.01	0.41 ± 0.18	0.03
Post-kick measures	Arm resumption distance (m)	4.69 ± 1.27	4.11 ± 0.51	0.58*
	Arm resumption velocity ($m.s^{-1}$)	1.55 ± 0.13	1.57 ± 0.21	-0.02
	Arm resumption time (s)	1.58 ± 0.70	1.24 ± 0.29	0.34*
	Surface distance (m)	5.36 ± 1.36	4.92 ± 0.66	0.44
	Surface time (s)	2.02 ± 0.74	1.77 ± 0.42	0.26
	Number of dolphin kicks	3.0 ± 1.78	-	-
	Dolphin kick distance (m)	2.23 ± 1.31	-	-
	Dolphin kick time (s)	1.34 ± 0.76	-	-
	5 m out-time (s)	1.80 ± 0.21	1.82 ± 0.21	0.02

* Denotes significance (p<0.05) using paired sample t-test

Significant differences were found in two of the five post-kick measures (see Table 5.1). Arm resumption distance and time occurred significantly further from the wall and later, respectively, following the dolphin kick turns when compared with the flutter kick trials. No differences were observed between arm resumption velocity for each subject's dolphin kick and flutter kick trials (group mean 1.57 $m.s^{-1}$ and 1.55 $m.s^{-1}$, respectively). Hence, swimmers in this study swam with equal horizontal velocity at the commencement of stroking during the dolphin kick and flutter kick trials. Whilst there was no statistically significant difference for surface distance and time between the two turn techniques, in the dolphin trials the swimmers surfaced 44 cm further from the wall and 0.26 s later, than during the flutter kick trials.

A Pearson product-moment correlation matrix outlining those variables that shared common variance following the turn and preceding the resumption of kicking can be found in Table 5.2. Significant negative correlations were found between 5 m out-times with peak force Y and X, wall exit velocity and leg kick resumption velocity. There was no significant correlation for the 5 m out-time with average swim velocity-in, WCT, peak force Z, and leg kick resumption distance and time. A multiple stepwise regression analysis was conducted to predict 5 m out-time. Significant independent variables were added to the model when a variable was determined to add predictability to the regression equation at an alpha level of $p<0.05$ (see Table 5.3). The best pre-kick predictors for 5 m out-time in order of importance were: wall exit velocity and peak Y force. These variables accounted for 59% of the variance in 5 m out-time. The relatively low percentage of variation (59%) in 5 m out-time explained by these variables is expected as this analysis did not account for the spontaneously selected distance and time, for resumption of kicking and stroking, in which large variations could exist.

Table 5.2. Pearson product-moment correlations for all variables preceding the resumption of kicking and 5 m out-time

	5 m out-time	**Av. swim Vel. in**	**WCT**	**Peak force Z**	**Peak force Y**	**Peak force X**	**Wall exit Vel.**	**Leg R Dis.**	**Leg R Vel.**	**Leg R time**
5 m out-time (s)	1	-.366	.140	-.353	-.483*	-.542*	-.653*	-.221	-.604*	.364
Average swim velocity in (m.s^{-1})		1	.087	-.102	.544*	.073	.294	.025	.152	-.334
WCT (s)			1	-.486*	-.169	-.418*	-.037	-.117	.326	.037
Peak force Z (N)				1	-.109	.288	.344	.130	.174	.019
Peak force Y (N)					1	.296	.065	.197	.245	-.195
Peak force X (N)						1	.449*	.130	.242	-.172
Wall exit velocity (m.s^{-1})							1	.136	.574*	-.229
Leg resumption distance (m)								1	-.152	.789*
Leg resumption velocity (m.s^{-1})									1	-.408*
Leg resumption time (s)										1

Note. Vel. = velocity; Dis. = distance; R = resumption

* Denotes significance ($p<0.05$)

Repeated measures ANOVA (using those variables identified in the regression equation as covariates) was conducted with 5 m out-time as the dependent variable. Results from the repeated measures ANOVA indicated significant effect in both covariates used (see Table 5.4). These variables were wall exit velocity and peak Y force. The adjusted marginal means for 5 m out-time by kick type were 1.809 ± 0.013 s and 1.812 ± 0.013 s, for the dolphin kick and flutter kick trials, respectively. Inclusion of the covariates in the comparison analyses also demonstrated no significant difference (p=0.880) between the dolphin kick and flutter kick turn types for 5 m out-time.

Table 5.3. Stepwise regression equation and results for prediction of 5 m out-time.

Variable	**Regression coefficient**	**Beta weight**	**R squared**	**Adjusted R-squared**
Wall exit velocity	-0.368	-0.625	0.427	0.403
Peak Y force	-2.11E-03	-0.442	0.621	0.588

Constant: 3.003

Table 5.4. Summary of repeated measures ANOVA.

Source	**Type 1 SS**	**df**	**Mean square**	**F**	**Sig.**
Wall exit velocity	0.445	1	0.445	14.259	0.003
Peak Y force	0.203	1	0.203	6.437	0.026
Between subject error	0.376	12	3.133E-02		
Kick	4.541E-05	10	4.541E-05	0.024	0.880
Within subject error	1.903E-02	10	1.903E-03		

Discussion

The participants were elite age-group competitors who could perform repeated effort swims consistently. Consistency of performance was regarded as integral to the comparison of the two turn techniques in order to credit any change in turn performance to the proposed technique variation. This consistency was demonstrated by the results of a comparison between each swimmer's first and second 50 m freestyle swim times (28.59 ± 1.65 s and 28.62 ± 1.73 s, respectively) for the trials using flutter kick wall exits. The trials incorporating the flutter kick exits were chosen for comparison as these swims were representative of the turning technique most commonly used by each swimmer. Therefore, consistency would more likely be demonstrated.

As found previously (Blanksby et al., 2004), the mean peak Y and X forces during push-off were shown to only represent approximately 5 to 15 % of the mean peak Z force. This result indicates that the majority of wall contact force was directed effectively for the required change in horizontal direction. Despite the mean peak Y force recorded for the dolphin trials averaging 10 N (9 %) more than the flutter trials, the absolute values of peak Y force did not indicate that subjects pushed off the wall with greater vertical force in an attempt to obtain greater depth for dolphin kicking.

Lyttle and Mason (1997) reported an average freestyle turn WCT of 0.29 ± 0.05 s and peak Z force of 1345.3 ± 236.5 N for three adult male swimmers of a national calibre (open age). These adult results represent substantially higher values than those recorded in the present study of younger age groups where WCT times of 0.44 ± 0.12 s and 0.49 ± 0.13 s and peak Z forces of 892.2 ± 246.8 N and 864.3 ± 252.9 N were recorded for the dolphin kick and flutter kick trials, respectively. These differences are attributed to differences in swimming ability, age, height and mass of the participants in the present study. Comparable force analysis techniques, allowing for the presence of pre-touch forces due to a bow wave, enabled valid comparison of WCT between the two studies.

As indicated above, direct comparison of technique differences between the dolphin kick turn and the flutter kick turn cannot occur until the actual point where kicking is resumed. Events leading up to this point could mask any variations but the current study revealed little difference between the techniques leading up to the point of kick resumption. Appropriate selection of the time to resume kicking is a voluntary skill that is related to experience. Irrespective of kick type, participants in the present study were shown to select non-significantly different time and distance from the wall to resume kicking for the two kicking techniques. However, the velocity at which kicking resumed during the dolphin kick trials was significantly less (0.17 $m.s^{-1}$) than during the flutter kick trials. A change in streamlining while preparing to initiate dolphin kicking could have resulted in a slowing down prior to the resumption of kicking during the dolphin trials. The period from resumption of kicking to 5 m out could therefore be isolated to allow direct comparison between the two kicking techniques.

The ability to maintain wall exit velocity at greater than free-swimming velocity for a longer period before commencing stroking is critical in completing a faster turn. Appropriate selection of kicking resumption time and velocity is important to utilise the benefits from the wall push-off. Resuming the kick too early negates the streamlined glide and momentary rest advantage while delaying kicking resumption requires extra energy to accelerate back to free-swimming velocity (Blanksby, Gathercole et al., 1996). Those swimmers who decelerate less following a turn need to have generated this velocity without producing detrimental increases in drag. Figure 5.1 represents a plot of mean velocity at wall exit, kick resumption and stroke resumption for the dolphin kick and flutter kick trials. Despite travelling 0.58 m further, and spending 0.34 s longer when kicking during the dolphin trials, the velocities at which arm resumption occurred for both wall exit techniques were similar (dolphin 1.55 ± 0.13 m.s^{-1} and flutter 1.57 ± 0.21 m.s^{-1}). The change in velocity from the resumption of kicking to the resumption of stroking during the flutter trials was equal to a decrease of 0.50 m.s^{-1} and occurred over a distance of 1.41 m and 0.83 s. This represents an average deceleration of 0.60 m.s^{-2}, as indicated by the line slope representing the flutter kick phase in Figure 5.1.

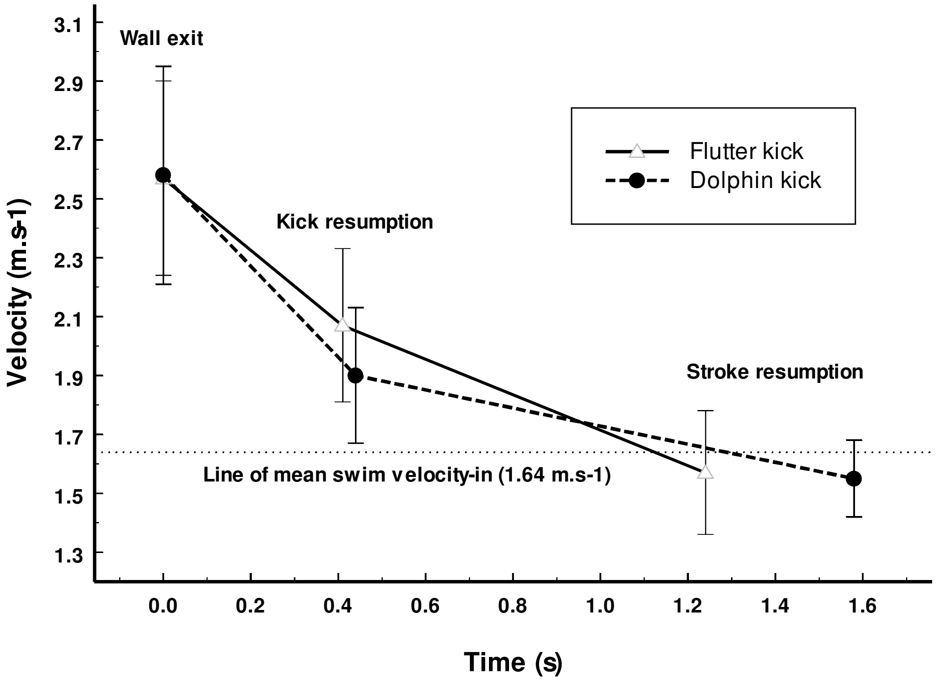

Figure 5.1. Dolphin kick versus flutter kick mean velocity at wall exit, kick resumption and stroke resumption.

From the resumption of kicking to the resumption of stroking during the dolphin trials there was a velocity decrease of 0.35 m.s^{-1} that occurred over a distance of 1.92 m and a time of 1.14 s. Thus, average deceleration was 0.31 m.s^{-2}, as indicated by the slope of the line representing the dolphin kick phase in Figure 5.1. Hence, velocity above that of free-swimming was maintained for longer during the kicking phase of the dolphin trials. Therefore, while dolphin kicking after a turn did not increase velocity, it slowed the swimmer more gradually than flutter kicking. This could be due to better streamlining and greater propulsion from the dolphin kick technique.

The number of kicks and rate of dolphin kicking could also influence dolphin kick turn performance. The mean number of dolphin kicks executed during the dolphin trials was 3.0 ± 1.78 kicks. This number of kicks equates to a dolphin kick rate of 2.24 kicks.s^{-1}. The mean number of dolphin kicks executed in Chapters 3 and 4 were 2.46 ± 1.07 and 2.45 ± 1.06, respectively. These numbers of kicks equate to dolphin kick rates of 1.68 and 1.79 kicks.s^{-1}. The likely explanation for this difference in dolphin kick rates is differences associated with age dependent factors such as greater strength, proficiency and practice. However, the faster kick rate observed in the present study may be linked with greater underwater dolphin kick efficiency. This, in turn, may have contributed to the non-significant difference observed between the dolphin and flutter kick turning techniques.

Generally, the preferred time to resume stroking following a start or turn should be when the horizontal velocity has decreased to equal that of free swimming velocity. The velocity at which arm resumption commenced during the present investigation was similar for both the dolphin and flutter kick trials (1.55 ± 0.13 m.s^{-1} and 1.57 ± 0.21 m.s^{-1}, respectively). These values were slower than the mean free-swimming velocity-in of 1.64 ± 0.11 m.s^{-1}) (see Figure 5.1). Hence, both groups tended to wait too long to resume arm stroking. Therefore, improved 5 m out-times are possible by more accurately selecting stroke resumption velocity through coaching and training. Despite this weakness, velocity above that of free swimming was maintained for longer when using the dolphin kick technique (see Figure 5.1). That is, if stroking had resumed when kicking velocity reached that of free swimming, the use of dolphin kicking would have remained advantageous because of the decreased deceleration (see Figure 5.1).

The time spent gliding; kicking and stroking to 5 m-out following the turn for the dolphin and flutter kick techniques are presented in Figure 5.2. Time spent kicking during the dolphin trials was shown to be greater and comprised 63.3 % of the time to 5 m-out compared with 45.6 % during the flutter kick trials. Despite little difference shown between the total times to 5 m-out, the technique methods used to achieve this result were different. That is, subjects remained submerged and engaged in kicking for a significantly longer period during the dolphin trials.

Valid statistical comparison of the dolphin kick and flutter kick turn methods required adjustment for any cumulative variation in performance before the resumption of kicking. Hence, those performance variables that were highly predictive of the 5 m out-time prior to kicking were identified from a stepwise regression analysis. The most predictive variables were wall exit velocity and peak Y force. Inclusion of these variables as covariates in a repeated measure ANOVA allowed adjustment for possible variations between the two techniques, prior to kicking resumption. Once statistically controlled for pre-kick performance variation, no significant difference was observed between the dolphin kick and flutter kick turn types for 5 m out-time. While the difference between the 5 m out-time means for the two turn techniques appear to vary only slightly (dolphin 1.80 s and flutter 1.82 s) and represent an improvement of only one percent over this distance, it could be significant in the context of a swimming race. Six of the 13 subjects recorded faster dolphin kick 5 m out-times than flutter kick 5 m out-times, while two subjects recorded the same 5 m out-time for the two techniques. These findings suggest that, for approximately half of the swimmers in the present study, the dolphin kick turn was a superior method of exiting the wall and resuming swimming during a 50 m maximal freestyle effort in a 25 m pool.

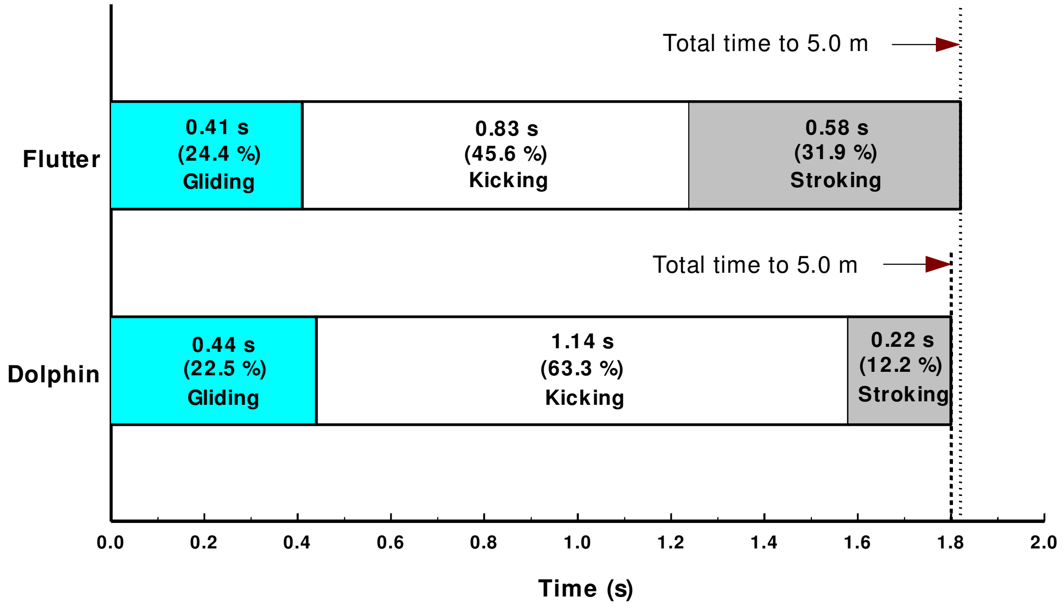

Figure 5.2. Schema of the time spent gliding, kicking, and stroking to 5 m out following the turn for the dolphin and flutter kick wall exit techniques.

Conclusion

This study showed that a tumble turn which used a dolphin kick off the wall was not significantly faster for 5 m out-time than when using a flutter kick off the wall. Neither did one technique result in a superior 50 m total time. The time spent kicking during the dolphin trials was significantly greater and comprised 63.3 % of the time to 5 m-out compared with 45.6 % during the flutter trials. During the underwater kicking phase of the turn, deceleration was less during the dolphin kick than in the flutter kick trials. Consequently, velocity above that of free-swimming was maintained for longer during the kicking phase of the dolphin turn trials. Whether one technique is universally superior to the other, and individual swimmers are better suited to one technique rather than the other, requires further investigation.

Chapter 6

Study 4: A Comparison of Lower Extremity Kinematics during Free-Swimming Underwater Kicking Techniques

Introduction

To improve performance, a swimmer must optimise all aspects of the event they are contesting. An optimal outbound turning technique requires maximising the distance achieved from the wall push-off by minimising the deceleration caused by drag forces (Lyttle et al., 2000). Therefore, selection of the appropriate time spent gliding, kicking and when to resume stroking (Blanksby, Gathercole et al., 1996; Carpinter, 1968; Lyttle & Benjanuvatra, 2003; Sanders & Byatt-Smith, 2003) and selection of the most effective kicking style (Lyttle et al., 2000) appears critical to reducing total turn time.

Anecdotal evidence suggests that free-swimming underwater dolphin kick is faster than underwater freestyle (flutter) kick. Subsequently, many swimmers adopt this technique following the start and turns in freestyle races. Lyttle et al. (2000) investigated net drag forces during tethered swimming from which inference regarding the effectiveness of these kicking styles following the start and turn was made. They reported no significant difference in drag between a prone freestyle kick, prone dolphin kick or a lateral dolphin kick, when towed at velocities 1.6, 1.9, 2.2, 2.5 and 3.1 m.s^{-1}, respectively. Underwater kicking kinematics and the relative individual strengths of each swimmer's kicking styles were not measured.

Previously, investigations into flutter or dolphin kicking kinematics have been made by either isolating the kick or from within the whole stroke, at the water surface (Barthels & Adrian, 1971; Bucher, 1975; Cavill, 1973; Fujiwara & Ogita, 1997; Kelly, 1973; Sheeran, 1980; Ungerechts, 1983a). More recent studies have explored kicking kinematics underwater, independently from the stroke (Arellano, Gavilan & Garcia, 1998; Shimonagata et al., 1997). Arellano et al. (1998) performed a comparison of the underwater undulatory movements (dolphin kick) in two separate body positions, prone (ventral) and on the back (dorsal). No significant differences were reported between the two kicking techniques for kick frequency, length, mean velocity and most joint angles. Significantly larger angles were observed at the shoulder at the start of knee extension and the knee at the end of knee extension for the ventral kicking technique.

Shimonagata et al. (1997) explored body oscillations and the temporal relationships of body parts during underwater dolphin kick using kinematic and electromyographic analysis. Data were recorded from three separate subjective swim velocities (fast, medium and slow) with results indicating the undulatory dolphin kick oscillations of the skilled swimmers travelled sequentially from the hand to the ankle. Oscillations from hand to hip were constrained in the unskilled swimmers as was determined by body segment phase angles and muscle activity patterns. Despite these findings, Shimonagata et al. (1997) failed to quantify the significance of upper body movements to underwater kicking performance. The significance of upper body movements to underwater dolphin kicking performance is presently unknown due to a lack of research. Contrary to the observations of Arellano et al. (1998) and Shimonagata et al. (1997) who investigated and reported whole body movements, current coaching practice suggests that limiting vertical upper body movement and kicking from the hips down will produce a faster underwater dolphin kick speed. Therefore, closer attention to the lower extremity in human underwater dolphin kicking appears warranted.

Alley (1952) reported large amplitude surface freestyle kicks to be superior to small amplitude freestyle kicks, while being towed at greater than free-kicking velocities. This finding indicates that larger kick amplitudes relate highly with increased kicking proficiency. Dolphin kick rates observed in the earlier work in this series (Chapters 3, 4 and 5) suggest underwater dolphin kick proficiency may be linked with kick style. Swimmers' usually select their kick amplitude, frequency and the subsequent kick amplitude - rate ratio based on what they feel provides maximal velocity. If larger kick amplitudes prove to be more efficient, optimal kick amplitude must exist beyond which efficiency begins to decrease. It is possible that the optimal kick amplitude may be a function of body length. Aquatic animal research has indicated that dolphin tail beat amplitudes do not exceed values greater than 25 % of their body length (Ungerechts et al., 1998). Therefore, the relationship between human anthropometry and absolute kick amplitude and frequency may provide insight into the optimal kick kinematics required for maximal underwater kick velocity.

Despite the investigations mentioned above, no known research has been conducted to examine the kinematic differences between free-swimming underwater dolphin and flutter kicking styles. Similarly, no research has attempted to quantify components of fast underwater kicking technique based on kinematic and a variety of anthropometric measures. Hence, the purpose of this investigation was to examine free-swimming underwater kicking styles and to identify technique and anthropometric characteristics that are predictive of fast underwater kicking.

Methodology

Sample

Subjects comprised 11 males of mean (±SD) height, 177.49 ± 8.13 cm; mass, 68.89 ± 10.71 kg; and age, 15.72 ± 3.58 yrs; and 6 females of mean height, 166.78 ± 4.02 cm; mass, 56.50 ± 6.08 kg; and age, 14.83 ± 1.17 yrs. Mean (±SD) personal best 50 m short course freestyle times for the male and female participants were 25.83 ± 1.29 (range 24.10 – 28.60) and 28.67 ± 0.27 (range 28.31 – 29.00), respectively. All male participants in this study had previously recorded a 100 m freestyle short course time of less than 60 s, while all female participants had previously recorded a 100 m short course time of less than 65 s. All participants were considered skilled and to possess adequate experience in dolphin and flutter kicking based on their swim times and the training required to perform at such levels.

Data collection

Participants were paired to form two equal lines from fastest to slowest, based on their 50 m short course freestyle personal best time. Every second pair was then switched across the lines at which time each participant was given a number according to their line and position (odd and even). Once in this order, the odd numbered participants were assigned to perform dolphin kick trials first and the even numbered participants were assigned to perform flutter kick trials first.

Each participant was then physically number coded and the hip knee and ankle joints were highlighted with pen markings on the right side of the body, using procedures identified by Plagenhoef (1971). The right foot was also land marked at the distal head of the fifth metatarsal. The distance between the hip (trochanterion) and the knee (femur/tibia joint line) markings was measured and recorded as thigh length. An example of participant land marking is presented in Figure 6.1. All participants wore swim caps during the test trials.

Figure 6.1. Participant with number coding and landmarking.

Warm-up

Prior to the data collection trials, a warm-up was undertaken consisting of a 400 m freestyle swim. Following the freestyle swim, 4 x 10 m underwater dolphin kick and 4 x 10 m underwater flutter kick swims, building to 100% max velocity by the fourth swim, were performed.

Underwater natural dolphin kick and flutter kick trials

Natural dolphin kick was defined as a participant's normal underwater dolphin kick technique in a prone position. Data collection trials began with participants assembling mid-pool, in order, where they were reminded to maintain their assigned kick order. Participants were required to attain maximum velocity in each swim trial. Using a push start from the bottom, participants were instructed to build underwater kick velocity and reach maximum velocity by the time they crossed a floor marker placed 7 m meters from the pool wall. Maximum kick velocity was to be maintained from this point through to the end of the pool. Each participant performed their randomly assigned kick type for their first two trials and then completed the remaining two trials with the other kick. A departure time of 15 seconds was used between participants who each repeated their kick trials every six minutes. Each kick trial was performed at a depth greater than 40 cm from the surface to eliminate the effects of surface wave drag (Lyttle et al., 1998). Swim depth was subjectively assessed via a video monitor and trials perceived to be performed less than 40 cm from the surface were repeated or discounted from the analysis. In most cases, where a swimmer failed to swim below the desired depth during their first trial, swim depth was rectified during the second trial. This eliminated the need for extra trials and potential fatigue effects that could influence performance. Side-on video images of all test trials were recorded and stored for analysis.

Modified underwater dolphin kick trials

Modified underwater dolphin kick trials were included in this investigation to examine the effect that kick amplitude and frequency have on kicking proficiency. Following completion of the underwater natural dolphin kick and flutter kick trials, participants were given 10 minutes instruction and practice at performing two modified underwater dolphin kicking techniques. Both modified dolphin kick techniques were performed in a prone position. The first of these techniques, 'small dolphin', involved using a small kick action with a high frequency. Specifically, participants were instructed to practise and then perform the small dolphin kick according to the following criteria: a fast kick; a small kick amplitude; small vertical movement of the feet; using maximum effort; at maximum velocity; with the arms extended (hands locked) and upper body held in a streamlined position. The second modified underwater dolphin kick technique, 'large dolphin', involved using a large kick action with a slower frequency. Specifically, participants were instructed to practise and then perform the large dolphin kick according to the following criteria: a large kick amplitude; large vertical movement of the feet; using maximum effort; at maximum velocity; with the arms extended (hands locked) and upper body held in a streamlined position. Two underwater dolphin kick trials using the small kick technique and two using the large kick technique were then performed according to their randomly assigned order. All modified kicking trials were performed and recorded using the methodology of the underwater natural dolphin and flutter kick trials. Participants were also required to perform the modified underwater kicking trials at maximal velocity.

Anthropometric tests

A level two-trained Kinanthropometrist recorded the following anthropometric measures, in accordance with the definitions and measurement procedures used by Norton and Olds (1996), from each participant within a two-week period following the swimming trials; standing and sitting height, tibiale laterale, tibiale mediale-sphyrion tibiale, trochanterion-tibiale laterale, trochanterion, foot length, biacromiale, transverse chest, bi-iliocristale, and body mass. Foot breadth was also recorded as maximal foot width while weight bearing.

Instrumentation

A Rosscraft Centurion anthropometry kit was used for the collection of all anthropometric measurements. Height was recorded using a portable stadiometer to an accuracy of 0.1 cm and Avery Berkel electronic scales were used to record weight to an accuracy of 0.01 kg.

Trials were recorded using a Panasonic MS5 S-VHS video camcorder set to record at 50 Hz. An exposure time of $500.s^{-1}$ was used and the video images were recorded on a Panasonic VCR (model AG-7350-E). The field of view was set to record the hip to foot complex over a minimum of two complete kick cycles. The camera was positioned in an underwater viewing window 5.4 m lateral to the swimmer's path and 5.0 m from the end of the pool. A schema of the equipment set-up is presented in Figure 6.2.

Camera positions placed further from an object being filmed minimises the risk of perspective error (Cureton, 1939). Poor image quality associated with underwater videography required each swimmer to remain relatively close to the camera during trials in this study (see Figure 6.2). This positioning, combined with the difficulty ensuring all swimmers remained the correct distance from the camera when free swimming, were considered potential causes of measurement error. For example, variation in swim plane of 25 cm relative to the reference (calibration) structure positioned 5.4 m from the camera equates to a perspective error of 4.6 %. Consequently, horizontal thigh length was digitised and used as the known calibration length for each participant trial. Detailed justification for using this method is presented in Appendix D.

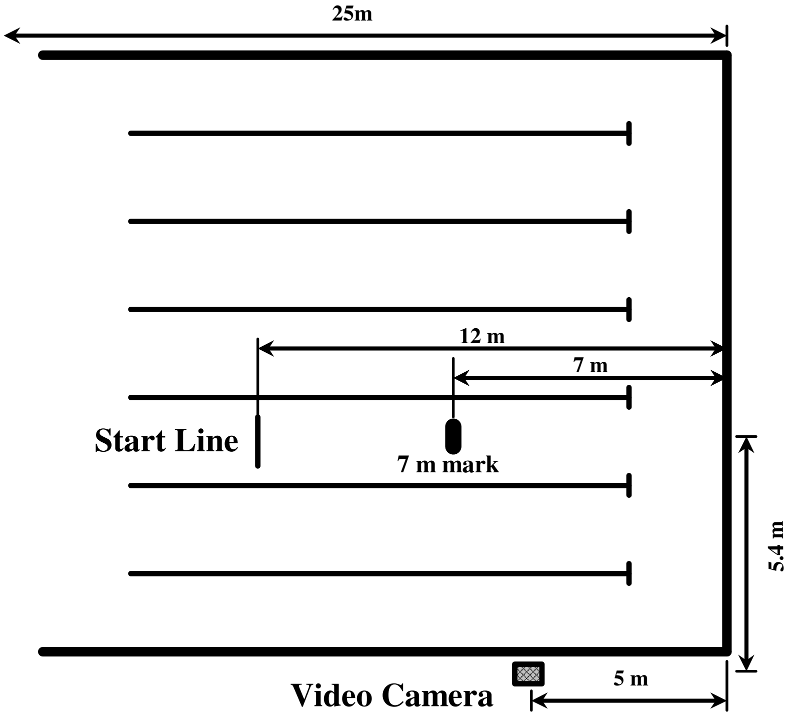

Figure 6.2: Schema for equipment set up.

Data analysis

Two-dimensional analysis via a Peak Motus 32 (Version 6.1) motion analysis system was used to digitise the lower extremity (single leg hip to foot segment) over one complete kick cycle. A kick cycle was defined as the period in which the ankle (lateral malleolus) travelled through one full up and down movement. This was determined qualitatively by visually identifying successive vertical ankle maxima from the video footage. A complete kick cycle nearest to the centre of the digitising screen was chosen for analysis. In view of current coaching practices for underwater dolphin kicking, investigation in the current study was de-limited to the lower extremity. Subsequently, hip (trochanterion), knee (femur/tibia joint line), ankle (lateral malleolus) and the foot (head of 5th metatarsal) were the landmarks digitised from which the following measures were computed for one kick cycle: time (s); horizontal hip displacement (cm) and velocity ($cm.s^{-1}$); vertical displacement of the hip, knee, ankle and foot (cm); and joint angle range of movement of the knee and ankle (degrees). Ten frames before and after each kick cycle were also digitised to eliminate end-point smoothing errors. All digitised data were then smoothed using a Butterworth filter with a Jackson-Knee optimal prescribed cut-off of 0.1 (Peak Motus 32, 2001). An example of a digitised frame with segment overlays is presented in Figure 6.3. A kick amplitude-rate ratio was calculated by dividing the vertical displacement of the foot (cm) by the time per full kick cycle (s). Further, adapted Strouhal numbers were calculated in accordance with the method used by Arellano et al. (2000). This dimensionless number represents the ratio of unsteady and steady motion and low values have been shown to indicate better performance, when applied to underwater dolphin kicking in humans (Arellano et al., 2000). The equation for the adapted Strouhal number is:

$$StN = A_{p-p} f / U$$

Where StN is the Strouhal number, A_{p-p} is the tail-beat peak-to-peak amplitude (the distance from the peak of the tail fluke up-stroke to the peak of the down-stroke), f the stroke frequency (Hz) and U the swimming velocity (Fish & Rohr, 1999, as cited in Arellano et al., 2003).

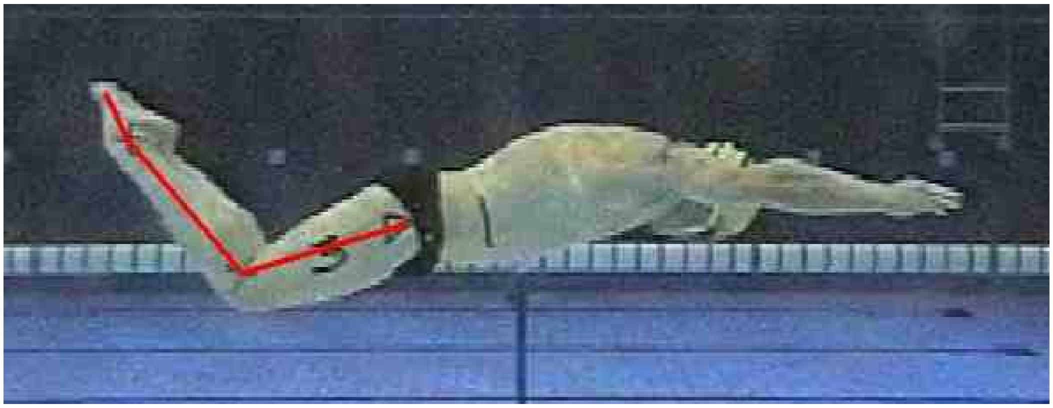

Figure 6.3. Swimmer with digitised landmarks and segmental overlays.

Statistical analyses

A two-way repeated measures ANOVA was used to analyse the data using horizontal kick velocity as the criterion measure. Gender and kick type (2 levels) were used in the model as between and within participant factors, respectively. Type III sums of squares, Bonferroni adjustment and an alpha level of p=0.05 were used. Violation of any statistical assumptions was tested using Box's M, Levene's and Mauchly's sphericity tests, while normality was assessed via examination of the residual plots. Greenhouse-Geisser corrections were used on the degrees of freedom where the critical assumption of sphericity was not met (Jaccard, Becker, & Wood, 1984). The different kick types were partitioned into three planned comparisons to examine kick velocity between the natural dolphin kick and each of the other three underwater kicking techniques.

Separate two-way repeated measures ANOVA's were performed on each kinematic variable for the natural dolphin and flutter kick trials. Natural dolphin was selected for this procedure, as it is more representative of a maturely developed skill and not manufactured as in the small and large dolphin swims. Gender and kick type (2 levels) were again used as between and within participant factors, respectively, with type III sums of squares and an alpha level of $p=0.05$. This analysis was performed to identify those performance measures that differed significantly between the two kick techniques. Procedural assumptions, normality and any corrections were assessed and applied, if necessary, as described above.

A Pearson product-moment correlation matrix was constructed to identify the relationship between variables for the natural dolphin kick trials. A multiple stepwise regression analysis was then conducted on the kick technique data that produced the fastest underwater kick velocity (natural dolphin), using horizontal velocity of the hip as the dependent variable. Measures were added to the model when a variable was determined to add predictability to the regression equation at an alpha level of $p<0.05$. This was performed to determine the overall predictive characteristics of the kinematic variables measured from underwater natural dolphin kicking and the anthropometric data.

Digitising a single trial 10 times was performed to assess digitiser reliability. Separate alpha correlation coefficient tests were performed on each of the following grouped variable measures: hip, knee, ankle and foot vertical displacements; maximum, minimum and mean horizontal hip velocities; and knee and ankle range of movements. The reliability analysis results demonstrated standardised alpha coefficients of greater than 0.997 for each grouped variable measure. Thus, high digitiser consistency was indicated. All data analyses were performed using an SPSS Statistical Analysis Package (version 10.0.5, 1999).

Results

The means and standard deviations for anthropometric measurements are listed in Table 6.1. Means and standard deviations for each of the measured kinematic variables by kick type are presented in Table 6.2. Box's M, Levene's and Mauchly's sphericity tests revealed no statistical procedural assumptions were violated. Similarly, Kolmogorov-Smirnov and Shapiro-Wilks statistics and inspection of residual plots indicated no normality assumptions were violated. Results indicated that a significant difference existed in horizontal kick velocity across all four underwater kick techniques. No kick by gender interactions were evident, however, the between subject effect of gender was shown to be significant (p=0.006) for horizontal hip velocity.

Table 6.1. Anthropometrical means (±SD) for male and female participants.

	Mean ±SD	
Anthropometric measures (cm)	**Male (n=11)**	**Female (n=6)**
Standing height	177.49 ± 8.13	166.78 ± 4.02
Sitting height	91.32 ± 5.20	85.60 ± 2.46
Trochanterion	92.25 ± 4.92	86.21 ± 4.03
Trochanterion-tibiale laterale	45.55 ± 2.67	42.93 ± 2.27
Tibiale laterale	46.70 ± 2.47	43.28 ± 1.99
Tibiale mediale-sphyrion tibiale	38.99 ± 1.64	36.83 ± 0.98
Foot length	26.97 ± 0.58	24.98 ± 0.63
Foot breadth	10.10 ± 0.53	9.20 ± 0.13
Biacromiale	38.96 ± 3.28	36.07 ± 1.86
Bi-iliocristale	29.30 ± 6.06	25.98 ± 0.89
Transverse chest	27.72 ± 1.50	25.63 ± 1.22
Anterior-posterior chest depth	19.56 ± 1.77	17.74 ± 0.93

Table 6.2. Means and standard deviations for each of the measured kinematics variables by kick type (n=17).

	Underwater kick technique			
Kinematic features	**Flutter**	**Natural Dolphin**	**Small Dolphin**	**Large Dolphin**
Time per kick cycle (s)	0.46 ± 0.03	0.49 ± 0.05	0.43 ± 0.06	0.63 ± 0.07
Kick frequency (kicks.s^{-1})	2.28 ± 0.18	2.15 ± 0.29	2.47 ± 0.39	1.65 ± 0.20
Horizontal displacement hip (cm)	57.94 ± 6.80	68.86 ± 11.67	57.47 ± 10.79	84.21 ± 15.83
Horizontal velocity hip (cm.s^{-1})	131.47 ± 15.23	145.94 ± 19.86	140.05 ± 19.58	135.21 ± 16.42
Vertical displacement hip (cm)	6.46 ± 2.21	9.01 ± 1.65	7.20 ± 2.25	14.75 ± 2.25
Vertical displacement knee (cm)	17.75 ± 3.30	22.55 ± 3.41	18.85 ± 3.99	30.87 ± 5.36
Vertical displacement ankle (cm)	37.11 ±3.41	35.91 ± 5.42	32.09 ± 7.10	50.33 ± 7.61
Vertical displacement foot (cm)	47.89 ± 4.67	46.66 ± 6.75	42.43 ± 8.36	61.54 ± 8.96
Knee range of movement (degrees)	59.32 ± 6.91	72.59 ± 6.23	66.26 ± 8.98	82.07 ± 7.43
Ankle range of movement (degrees)	33.95 ± 6.44	42.93 ± 9.43	37.49 ± 8.81	48.58 ± 10.96
Kick amplitude-rate ratio	107.16 ± 15.62	98.37 ± 15.06	102.78 ± 18.60	99.61 ± 13.51
Strouhal number	0.84 ± 0.10	0.68 ± 0.09	0.74 ± 0.07	0.75 ± 0.09

Planned comparison within the repeated measures ANOVA and inspection of the means showed horizontal kicking velocity (as indicated by horizontal hip velocity) to be significantly faster for the natural dolphin kick compared with each of the other three underwater kicking techniques (see Table 6.3). For separate two-way repeated measures ANOVAs on each kinematic variable for the natural dolphin and flutter kick trials (see Table 6.4), significant differences were observed between the natural dolphin and flutter kick techniques in 9 of the 12 parameters measured from one complete kick cycle (up- and down-stroke). For the dolphin kick technique, these were: greater horizontal hip displacement and velocity; greater vertical displacement of the hip, knee and ankle; increased range of movement at the knee and ankle; a larger kick amplitude-rate ratio; and a higher Strouhal number. The time taken to complete one kick cycle and kick frequency (number of kicks per second) was not significantly different between the two underwater kick techniques.

Table 6.3. Mean horizontal hip velocity and planned comparison difference between the kicking techniques.

Kick type	**Mean horizontal hip velocity (cm.s^{-1})**	**Planned comparison**	**Sig. (p)**
Natural dolphin	144.88	-	-
Flutter	129.23	Nat. dol. > flutter	0.000
Small dolphin	139.61	Nat. dol. > small dol.	0.005
Large dolphin	134.15	Nat. dol. > large dol.	0.000

Note: Nat = natural; dol = dolphin.

Table 6.4. Summary results of separate ANOVA on performance variables by kick type (dolphin and flutter) and gender.

Variable	**Source**	**Mean square**	**F**	**Sig. (p)**
Time per kick cycle	Kick Type	3.297E-03	2.069	0.171
	Kick x Gender	8.994E-03	5.613	0.032*
	Gender	2.310E-04	0.086	0.773
Kick frequency	Kick Type	4.039E-02	1.062	0.319
	Kick x Gender	0.277	7.279	0.902
	Gender	1.112E-03	0.016	0.000*
Horizontal displacement hip	Kick Type	702.918	37.365	0.000*
	Kick x Gender	305.916	16.341	0.001*
	Gender	1549.414	14.791	0.002*
Horizontal velocity hip	Kick Type	1654.252	50.418	0.000*
	Kick x Gender	100.044	3.049	0.101
	Gender	8238.716	21.610	0.000*
Vertical displacement hip	Kick Type	45.775	17.469	0.001*
	Kick x Gender	2.350	0.897	0.359
	Gender	7.878	2.114	0.167
Vertical displacement knee	Kick Type	157.527	24.212	0.000*
	Kick x Gender	10.195	1.567	0.230
	Gender	190.261	19.305	0.001*
Vertical displacement ankle	Kick Type	18.867	6.432	0.023*
	Kick x Gender	39.585	13.495	0.002*
	Gender	412.923	16.382	0.001*
Vertical displacement foot	Kick Type	18.315	4.146	0.060
	Kick x Gender	47.981	10.860	0.005*
	Gender	799.975	19.735	0.000*
Knee range of movement	Kick Type	1187.913	40.331	0.000*
	Kick x Gender	91.557	3.108	0.098
	Gender	9.508	0.175	0.681
Ankle range of movement	Kick Type	528.738	16.467	0.001*
	Kick x Gender	49.125	1.530	0.235
	Gender	104.971	1.088	0.314
Kick amplitude-rate ratio	Kick Type	480.866	6.629	0.021*
	Kick x Gender	77.513	1.069	0.318
	Gender	4184.463	28.670	0.000*
Strouhal Number	Kick Type	0.159	42.084	0.000*
	Kick x Gender	0.006	1.462	0.245
	Gender	4.060E-04	0.029	0.867

* denotes significant difference between dolphin and flutter underwater kick techniques

Significant ($p<0.05$) gender differences between the natural dolphin and flutter underwater kick techniques were observed. The males demonstrated significantly: higher kick frequency; greater horizontal hip displacement and velocity; greater vertical displacement of the knee, ankle and foot; and larger kick amplitude-rate ratios than the females. No significant gender differences were observed for: time per kick cycle; vertical displacement of the hip; and range of movement of the ankle and knee; and Strouhal number. The presence of significant kick by gender interactions from the comparison of natural dolphin and flutter kick trials indicates any kinematic differences between kick types is not constant across the males and females. Significant ($p<0.05$) interactions were observed for time per kick cycle, horizontal hip displacement and vertical displacement of the ankle and foot.

Natural dolphin was shown to be a significantly faster (horizontal hip velocity) method of underwater kicking. Therefore, all further analyses were conducted on data from this kick technique in an attempt to identify parameters that contribute to fast underwater dolphin kick velocity. A Pearson product-moment correlation matrix relating horizontal hip velocity to the kinematic and anthropometric measures for the natural dolphin trials is presented in Table 6.5.

The best kinematic predictors of horizontal kick velocity in order of importance were: horizontal hip displacement, time per kick cycle and kick frequency. As the calculation of velocity is determined by dividing displacement over time, the highly predictive nature of horizontal hip displacement and time per kick cycle were not unexpected. Consequently, a multiple stepwise regression on the kinematic measures was repeated with horizontal hip displacement and time per kick cycle omitted from the analysis. Results from this procedure revealed vertical displacement of the ankle (larger kick amplitude) and range of movement of the ankle accounted for 65% (Adjusted R^2 = 0.65) of the variance in horizontal kick velocity. The best anthropometric predictor of horizontal kick velocity (horizontal hip velocity) during the natural dolphin kick trials was foot width, which accounted for 57% (Adjusted R^2 = 0.57) of the variance in horizontal kick velocity.

Table 6.5. Correlations of kinematic and anthropometric variables with horizontal hip velocity for natural dolphin kick trials.

Variables	**Correlations**
Time per kick cycle	.017
Kick frequency	-.125
Horizontal displacement hip	.825*
Vertical displacement hip	.226
Vertical displacement knee	.559*
Vertical displacement ankle	.676*
Vertical displacement foot	.675*
Knee range of movement	-.026
Ankle range of movement	.252
Kick amplitude-rate ratio	.714*
Standing height	.540*
Sitting height	.494*
Mass	.468*
Trochanterion	.564*
Trochanterion-tibiale laterale	.508*
Tibiale laterale	.580*
Tibiale mediale-sphyrion tibiale	.529*
Foot length	.756*
Foot breadth	.722*
Biacromial	.414
Biiliocristale	.310
Transverse chest	.494*
Anterior-posterior chest depth	.629*
Strouhal number	-.413 (p=0.09)

* denotes significant correlation at the 0.05 level of confidence.

Lastly, kinematic and anthropometric measures were assessed for predictability of horizontal kick velocity. Horizontal hip displacement and time per kick cycle were again omitted from the analysis. Results from this procedure indicated that the combination of foot width, ankle range of movement, vertical displacement of the foot and vertical displacement of the ankle, accounted for 87% (Adjusted $R^2 = 0.869$) of the variance in horizontal kick velocity (see Table 6.6).

Table 6.6. Multiple stepwise regression equation and results for prediction of horizontal swim velocity when swimming underwater natural dolphin kick, using selected kinematic and all anthropometric measures.

Variable	**Regression coefficient**	**Beta weight**	**R squared**	**Adjusted R-squared**
Foot width	26.314	0.686	0.596	0.569
Ankle range of movement	1.270	0.510	0.709	0.667
Vertical displacement foot	5.487	1.858	0.842	0.805
Vertical displacement ankle	-5.748	-1.496	0.901	0.869

Constant: -216.509.

Discussion

Data collection and treatment in the present investigation was limited to two-dimensional analyses. It is possible that the vertical oscillations of human legs during underwater dolphin kicking are not linear but include some curvilinear motion. Therefore, interpretations of the findings from this investigation should be considered within the context of this limitation.

Underwater free-swimming velocity was compared between four separate underwater kick styles: natural dolphin; flutter; small dolphin and large dolphin. A significant difference was found to exist across all four-kick techniques for velocity, suggesting variations in efficiency between the styles. Significant gender differences were observed across the four kick styles and are believed to be representative of normal differences in swimming ability rather than a male-female gender imbalance. Because males generally swim faster than females, the same trend is likely to occur in underwater kicking ability. Comparisons revealed the natural dolphin kick to be a significantly faster method of underwater kicking than flutter and small and large dolphin kicking techniques. However, it is acknowledged that the small and large dolphin kick techniques measured within this study were manufactured and did not represent mature movement patterns. Consequently, swimmers in this investigation performed best at what they had practised. Since Chapter 4 showed that dolphin kicking performance changed with practice, one could assert that there would be a good possibility of improvement in the smaller and larger kicking conditions if they were practiced. With practice, one or both might emerge as even better than the current best form. Furthermore, the superiority of unpractised modified dolphin kicking techniques to flutter kicking warrants their further investigation.

The present investigation also represents the first kinematic comparison of underwater dolphin and flutter kicking techniques. A marked difference was observed between the two underwater kick techniques with significant difference shown in seven of the ten kinematic parameters measured. Appreciably, underwater dolphin kicking was shown to be significantly faster than underwater flutter kicking, despite exhibiting similar kick frequencies. Assuming analysis of one leg flutter kick is representative of total lower body movement during that form of kicking, the difference in underwater kick velocity between the two techniques appears due to greater vertical displacement of the hip, knee, ankle and greater range of movement at the knee and ankle. Sheeran

(1980) also found a significant difference in knee range of movement between flutter and dolphin kicking, using electrogoniometers. However, significant difference between the two kick styles was not shown for ankle range of movement. Sheeran (1980), however, failed to note whether kicks were performed at the surface or underwater. Therefore, this omission limits the comparison of results and subsequent strength of conclusions regarding knee and ankle range of movement for flutter and dolphin kicking.

Significantly greater vertical displacement of the hip, knee, and ankle observed for the dolphin kick trials indicates that kick amplitude relates strongly with increased whole body, horizontal underwater kick velocity. This finding supports the earlier work of Alley (1952) who reported large amplitude surface freestyle kicks to be superior to small amplitude freestyle kicks. However, optimal underwater flutter kicking amplitudes are also yet to be identified and reported. Further, it is not known whether an underwater flutter kick with similar kick amplitude to that of the dolphin kick would produce a similar kicking velocity.

The absence of kick by gender interaction for horizontal hip velocity (criterion measure) and the presence of kick by gender interactions observed for several other kinematic measures suggest the reasons for differences in kick types for horizontal velocity are not the same for males and females. That is, males and females possessed technique variations within each kick type. These variations are possibly due to anatomical or strength differences. Low subject numbers in the present study prevents accurate discrimination between genders being performed for anthropometry, while strength measures were not obtained. Future research may well consider a larger sample and incorporate strength testing to assist discriminating between genders for underwater kicking performance.

Many investigations of the physical characteristics of successful male swimmers have shown them to have relatively large feet (Bloomfield & Sigerseth, 1965; Carter, 1966; Carter & Ackland, 1994). The stepwise multiple regression procedures in the present study found that foot breadth was the best predictor of underwater natural dolphin kick horizontal swim velocity, accounting for 57% of the variance (adjusted $R^2 = 0.569$). A significant positive correlation was also found between foot breadth and horizontal swim velocity ($r = 0.722$). This result indicates that those swimmers who possess wider feet are more likely to dolphin kick underwater with greater velocity. Grimston and Hay (1985) reported foot cross sectional area to be significantly related to stroke length for 12 male college swimmers in events ranging 50 to 1000 yards (45.7 to 914.4 m). Similarly, Vervaecke and Persyn (1979) found length, breadth and the surface of the sole of the foot to differ significantly between the top 25 % and lower 25 % of performers during tethered breaststroking. Foot dimension is determined almost exclusively by genetic factors (Bouchard, Demirjian, & Malina, 1980) and cannot be developed through training. Results in the present study further support the concept proposed by Grimston and Hay (1985) that selection of competitive swimmers might well focus on genetically determined structural factors.

Ankle flexibility is widely regarded to play an important role in kicking velocity (Cureton, 1930; Engesvik, 1992; Hull, 1990; Maglischo, 1993; Robertson, 1960). In contrast, Mookerjee, Bibi, Kenney and Cohen (1995) investigated the relationship between isokinetic strength, flexibility and flutter kicking velocity in female college students and found no significant correlation between flutter kicking times and plantar and dorsiflexion. Ankle range of movement was the second factor included in the stepwise regression equation in the current investigation. However, when assessed in isolation, a non-significant correlation ($r = 0.252$) was found between ankle range of movement and horizontal swim velocity. This result does not support Barthels and Adrian (1971) who suggested the development of flexibility for greater plantar flexion proves more beneficial than the development of lower leg strength when dolphin kicking. Ungerechts et al. (1998) also speculated increased ankle flexibility with the potential for greater efficiency of oscillatory swimming motion.

A focus of this investigation was to examine the concepts of free-swimming underwater kick frequency and amplitude. Despite a paucity of research, previous work in this series (Chapter 3) showed the fastest 33 % of dolphin kickers demonstrated a mean underwater dolphin kick frequency of 1.88 kicks.s^{-1} compared to 1.44 kicks.s^{-1} for the slowest 33 %. Arellano et al. (2000) also demonstrated higher underwater dolphin kick frequencies for better-performed swimmers. However, morphological differences and differences in swimming abilities (international vs. national age-group level swimmers) between groups were likely to have confounded this finding. In the present study, the absence of kick frequency from the regression equation for underwater natural dolphin kick horizontal velocity indicates that kick rate is of lesser importance than other variables. While kick rate appears to have minimal bearing on underwater human dolphin kick velocity, a dolphin's swimming velocity increases with tail beat frequency and becomes more asymmetric as velocity increases (greater emphasis on the down beat) (Ungerechts et al., 1998). This contrast provides evidence to suggest a weakness in analogising human dolphin kicking to the swimming action of marine dolphins.

Despite obvious differences in structural design between dolphins and humans, oscillatory movement patterns observed in dolphin swimming may provide possible application to human swimming. Ungerechts et al. (1998) reported that dolphin tail beat amplitudes do not exceed values greater than 25 % of their body length, while values approximating 20 % in have been reported for other fish species (Hertel, 1966). These findings suggest optimal undulatory kick amplitudes and frequencies could exist for the production of maximal undulatory swimming velocity. Swimmer dolphin kick amplitude (vertical foot displacement) in the present study was found to represent 27.5 % of standing height. In contrast, Arellano et al. (2000) reported dolphin kick amplitude percentages related to body heights of 34.31 % and 36.58 % for international and national level swimmers, respectively. The results of Arellano et al. (2000) suggest that faster underwater dolphin kicking is generated from smaller kick amplitudes relative to height. However, comparison between the current study and that of Arellano et al. (2000) does not support this theory as swimmers in the current investigation kicked with slower velocity while using smaller kick amplitude relative to height ratios. This is yet a further feature that distances human dolphin kicking from the oscillatory propulsive movements of mammalian dolphins.

The use of kick amplitude relative to standing height percentages in humans does not allow appropriate comparison to values recorded in some aquatic animals. That is, this measure is not representative of true swimming body length as the arms are usually extended above the head during underwater kicking. Hence, the calculation of kick amplitude to streamlined height ratios would provide comparative measures with other aquatic swimmers. Furthermore, streamlined height could be measured as easily as that of standing height, from which coaches could determine individual swimmer optimal kick amplitude heights, should they be found to exist. With few studies investigating the relationship between underwater kick amplitude relative to body height, further research to determine optimal underwater dolphin kick amplitudes is warranted.

Arellano et al. (2003) reported better swimmers to have lower UUS Strouhal numbers. Further, a significant and negative correlation was found between Strouhal number and velocity of the CM ($r = -0.639$). In contrast, the current study demonstrated a lower and non-significant relationship between Strouhal number and horizontal hip velocity for UUS ($r = -0.413$, $p = 0.09$). However, the relationships between kick amplitude; kick frequency and swimming velocity, from which the Strouhal number is derived, cannot be determined from this function. Hence, its use in determining optimal UUS technique appears limited.

Vertical displacement of the knee, ankle and foot were all significantly correlated with horizontal swim velocity, whereas vertical hip displacement was not ($r=0.226$). This result, combined with non-inclusion in the stepwise regression equation, indicates that vertical displacement of the hips is of lesser importance to horizontal dolphin kicking velocity. This result contrasts with the observations of Shimonagata et al. (1997) and Arellano et al. (1998) who reported increasing amplitude, whole body wave motions travelling from hand to foot during underwater dolphin kicking by skilled swimmers. The present findings support current coaching trends in underwater dolphin kicking where swimmers are instructed to minimise upper body movements and kick from the hips down.

The combination of foot width, ankle range of movement and vertical displacement of the foot and ankle were shown to account for 87 % of the variance in horizontal swim velocity when underwater natural dolphin kicking. These data indicate that, when combined appropriately, optimising these parameters would produce faster underwater dolphin kicking velocity. Therefore, coaches should not neglect the potential benefits that may be gained by increasing the vertical displacement the foot and ankle travel during underwater dolphin kicking.

The relative merits of underwater dolphin or flutter kick and the application of kick style to strategy following the turn is of interest to both swimmer and coach. The present work has enabled superior kick style and important technique characteristics during free-swimming underwater kicking to be identified. The relationship and transfer of the present findings to velocities greater than free-swimming are not known. Lyttle et al. (2000) reported between 2.2 and 1.6 $m.s^{-1}$ as the optimal velocity to resume kicking following a turn. Also, net drag forces during towing revealed no significant difference between underwater kick styles despite dolphin kick consistently producing better net forces than flutter kick. To further quantify differences between underwater kicking styles and identify technique characteristics conducive to efficient kicking at velocity higher than free-swimming, kinetic and kinematic analyses of underwater kicking at velocity ranges experienced following the turn warrant investigation.

Conclusion

Minimising the deceleration caused by drag force and maximising the distance obtained following a wall push-off is critical to optimising the outbound phase of a turn. Selection of the appropriate underwater kicking technique is equally important. The results of this study indicate that for this sample, free-swimming underwater dolphin kick is superior to that of flutter and two, unpractised modified dolphin-kicking techniques. Greater foot width and greater vertical displacement of the ankle and foot were shown to be highly predictive of faster underwater dolphin kick. Therefore, increased vertical movement of the foot and ankle during kicking are deemed important considerations for coaches and swimmers. Further research is required to quantify differences in underwater kick styles and to identify technique and anthropometric characteristics suited to efficient underwater kicking, at velocity ranges experienced following the starts and turns.

Chapter 7

Study 5: Kinetic and Kinematic Analysis of Underwater Gliding and Kicking

Introduction

To increase turn efficiency a swimmer must use the increased velocity gained from the wall push off to their advantage. Inappropriate selection of and inefficiencies in underwater kick style, technique and kick resumption time can all contribute to less than optimal turn exit performance due to energy losses caused by increased drag.

Numerous investigations have explored drag resistance in water either by mathematical estimation or from towing swimmers through a variety of positions, stroke techniques and velocities (Benjanuvatra et al., 2002; Clarys, 1985; Clarys & Jiskoot, 1975; Counsilman, 1955; Glazkov & Dementyev, 1977; Hollander et al., 1986; Karpovich, 1933; Kent & Atha, 1971; Kolmogorov & Duplishcheva, 1992; Maiello et al., 1998; Toussaint, et al., 1989; van Tilborgh et al., 1983). Until recently, however, the relative merits of different streamlined gliding and kicking techniques and selection of the correct time for stroke resumption following the turn were unknown. Lyttle et al. (2000) theoretically and empirically determined that the optimal glide and kicking paths consist of swimmers pushing off from the wall at and maintaining a glide depth of approximately 0.4 m. This equates to a glide time of 0.4 s over the first 1 m travelled, after which swimmers should ascend gradually to the surface and begin stroking at race pace. Lyttle et al. (2000) also proposed for experienced swimmers that kick resumption should occur between the velocities of 2.2 and 1.9 $m.s^{-1}$ that represents between approximately 1.1 and 1.5 m or between 0.45 and 0.65 s of gliding. Despite a trend by many swimmers towards adoption of the prone dolphin kick, no significant difference was observed between three underwater kicking techniques (prone freestyle, prone dolphin and lateral dolphin), suggesting swimmers should adopt the technique in which they are most proficient (Lyttle, 1999).

Assessment of underwater kicking proficiency for many swimmers may be difficult to ascertain, particularly at higher velocities. Further, knowledge of critical components of efficient underwater kicking technique at velocities higher than those achieved during swimming are yet to be determined. A previous study in this series indicated free-swimming underwater dolphin kick to be superior to flutter kicking (Chapter 6). Results from that investigation also suggest that particular anthropometric attributes contribute to efficient dolphin kick. However, maximal underwater free-swimming kicking velocity is lower than the velocities associated with wall push-off following the turn. Identification of key elements of efficient underwater kicking at those velocities experienced following the turn may serve to improve overall turn performance through appropriate underwater kick technique selection and / or improvement.

Hence, there is a need to explore the kinematics of underwater kicking at velocities commensurate with competitive swim turn exits in order to identify proficient underwater kicking mechanics and subsequent efficiency. Therefore, the primary aim of this investigation was to examine underwater kicking styles and to identify technique and anthropometric characteristics that are predictive of efficient underwater kicking while towed at velocities representing those experienced during freestyle turn wall exits.

Methodology

Sample

Eighteen experienced male swimmers volunteered as participants. The average number and duration of training sessions currently participated in, average years spent competing at State and National levels, and average personal best times for long-course 50 m freestyle, are presented in Table 7.1. Unlike Lyttle et al. (2000), selection of participants with specific body shapes and dimensions to minimise variation in drag resulting from differences in body form was not conducted. Conversely, a variety of body shapes and sizes were desired to assist in identifying if any anthropometrical relationships exist with efficient underwater dolphin and flutter kicking. However, to investigate the potential influence body form may have on total drag force; the three body form measures used by Lyttle et al., (2000) were selected to represent the three components of drag. These measures were chest girth (form drag), surface area (frictional drag) and a slenderness index (wave drag). The inclusion of these variables as covariates in some statistical analyses were performed in an attempt to co-vary for differences in drag due to variations in body size, while maintaining some anthropometric variation between participants. The means, SDs and ranges for participant age, anthropometric and body form measures are presented in Table 7.2.

Table 7.1. Means (±SD) and ranges for the number and duration of training sessions, years spent competing at State and National level, and long-course 50 m freestyle time.

	Mean ± SD	**Range**
Training sessions per week	6.67 ± 2.59	1.0 - 11.0
Training session duration (hrs)	2.00 ± 0.51	1.0 - 2.5
State Competition (years)	6.17 ± 1.79	4.0 - 10.0
National Competition (years)	3.50 ± 1.76	1.0 - 6.0
50 m Freestyle Time (s)	25.96 ± 0.79	24.80 - 27.50

Table 7.2. Means (±SD) and ranges for age and anthropometric measures.

	Mean ± SD	**Range**
Age (yrs)	18.06 ± 2.24	15.0 - 22.0
Mass (kg)	75.52 ± 7.19	57.0 - 86.8
Height (cm)	180.95 ± 4.99	173.1 - 190.1
Streamlined Height (cm)	246.62 ± 6.88	236.0 - 259.0
Trochanterion to Tibialis lateralis length (cm)	45.04 ± 2.12	42.05 - 49.75
Tibialis Lateralis to floor length (cm)	49.06 ± 2.12	45.45 - 53.45
Trochanterion to floor length (cm)	94.10 ± 4.00	88.4 - 103.2
Foot length (cm)	27.25 ± 1.00	25.55 - 29.05
Foot width (cm)	10.14 ± 0.37	9.50 - 10.80
Biacromial breadth (cm)	42.17 ± 1.50	39.65 - 44.65
Anterior-Posterior (A-P) chest depth (cm)	20.48 ± 1.06	18.8 - 23.35
Chest girth (cm)	99.66 ± 5.36	85.8 - 109.1
Waist girth (cm)	78.25 ± 3.59	71.2 - 84.55
Gluteal girth (cm)	94.44 ± 3.98	82.45 - 100.45
Calf girth (cm)	37.73 ± 2.30	32.95 - 42.55
Body surface area (m^2)	1.70 ± 0.10	1.46 - 1.85
Slenderness index ($cm/kg^{1/3}$)	42.87 ± 1.10	41.30 - 45.73

Data collection

Data collection occurred over a two-week period at the University of Western Australia's School of Human Movement Studies. Approval from the University of Ballarat and the University of Western Australia Human Research Ethics Committees and informed consent from all participants was obtained prior to commencement of the trials.

Anthropometric Measurements

All participants were measured for anthropometric dimensions in accordance with the measurement procedures used in Chapter 6. In the present investigation, however, these assessments took place on the same day as the swim test trials. These measurements included: standing and sitting height, tibiale laterale, tibiale mediale-sphyrion tibiale, trochanterion-tibiale laterale, trochanterion, foot length, biacromiale, transverse chest, bi-iliocristale, foot breadth and body mass. In addition, streamlined length was measured and recorded as total body length from the toes to fingertips, while lying prone with the arms extended above the head (torpedo position).

Towing Trials

Many of the participants used in this study had previously participated in similar studies and were familiar with the towing task. However, several familiarisation trials were given and test trials repeated until the desired body position and depth were obtained for each trial condition.

Before swim testing, each participant was physically number coded and land marked in accordance with the procedures outlined in Chapter 6. That is, the hip, knee and ankle joint centres were land marked with pen markings on the right side of the body, using procedures identified by Plagenhoef (1971). The distal head of the fifth metatarsal of the right foot was also land marked. The distance between the hip (trochanterion) and the knee (femur/tibia joint line) markings was measured and recorded as thigh length.

At separate test session times, each participant was towed at three separate velocities (1.6, 1.9 and 2.2 $m.s^{-1}$), along the length of a 25 m pool at a depth of 0.5 m. Previous research by Lyttle et al. (1999) revealed no significant difference in passive drag between the depth of 0.4 and 0.6 m. Hence, a towing depth as close to 0.5 m as possible was chosen for the towing trials.

Lyttle et al. (2000) found that net drag force, measured during towing, was significantly reduced from that recorded in a passive streamlined glide when kicking was employed at towing velocities of 1.6, 1.9 and 2.2 $m.s^{-1}$. No significant differences between kicking and gliding were observed at a towing velocity of 2.5 $m.s^{-1}$, while net drag forces during kicking were found to be significantly greater than gliding at 3.1 $m.s^{-1}$. Lyttle (1999) defined the highest velocity at which kicking produces less net force than the streamlined position as the ‘cross-over’ velocity, that is, a swimmer would create more active drag than propulsion if an equal or greater negative net force were recorded during kicking than in the streamlined glide position. Lyttle et al. (2000) found the optimal range to resume kicking (cross-over velocity) to be between 1.9 and 2.2 $m.s^{-1}$. Lyttle et al. (2000) also stated that the cross-over velocity at which kicking becomes detrimental would occur at higher towing velocities as swimming proficiency increased. Subsequently, towing velocities of 1.9, 2.2 and 2.5 $m.s^{-1}$ were used in the present study to ensure adequate range of towing velocity to accommodate variances in swimming proficiency.

Towing velocity was randomised, as was the order of tow type (glide, dolphin and flutter kick) between participants. Towing depth was monitored using the procedure developed by Lyttle et al. (2000) where images from an underwater video camera, positioned perpendicular to the swimmer’s line of motion, were observed to ensure the desired depth (between 40 and 60 cm) and body position throughout the towing trial. Feedback from the video image regarding depth was provided to swimmers following each trial. Trials performed outside this range were repeated. All trials were performed with maximal kicking effort and participants were encouraged to use their natural underwater kicking technique with no limitations placed on the rate or amplitude of the kicks.

Instrumentation

The towing device used in the present study was developed at The University of Western Australia's School of Human Movement Studies. This device was first used and published as a technical note by Lyttle et al. (1999). The towing device system was designed to quantify the drag experienced by the swimmer at pre-determined velocities and depths. This was achieved by towing swimmers along the length of a 25 m pool using a servo controlled mechanical winch. Velocity was controlled via a variable control unit, adjustable to 0.05 $m.s^{-1}$. Horizontal depth was controlled throughout each trial via a system of adjustable pulleys, while a waterproofed load cell containing four strain gauges measured the drag forces resisting towing. A voltage-to-frequency converter transformed the amplified strain gauge voltage signal to a frequency signal that was then transmitted to a Realistic FM receiver/demodulator on the pool deck. Following conversion back to a voltage signal, each signal was collected at 200 Hz for 10 s on a PC computer, and processed using the AP30 force analysis program (Pearce, 1996). A detailed description of the towing device is presented in Appendix C.

Two-dimensional analyses of the underwater kicking were performed in accordance with the procedures used in Chapter 6. All raw video derived data were smoothed using a Butterworth filter with a Jackson-Knee optimal prescribed cut-off of 0.1 (Peak Motus 32, 2001). The following measures were computed for one kick cycle: time (s); horizontal hip displacement (cm) and velocity ($cm.s^{-1}$); vertical displacement of the hip, knee, ankle and foot (cm); and joint angle range of movement of the knee and ankle (degrees). In addition, a kick amplitude / streamline height percentage ratio was calculated by dividing the vertical displacement of the 5th metatarsal by the streamline height and multiplying by 100. High digitiser reliability (alpha correlation coefficients > 0.997) was previously demonstrated for this method of analysis (Chapter 6).

Statistical analyses

Descriptive statistics (Means, SD) for the net forces recorded at each velocity for the streamlined glide, flutter and dolphin kicking conditions were calculated. The net force difference between the prone streamlined glide and the flutter and dolphin kick conditions were calculated for each subject by subtracting the flutter and dolphin net forces from the net force recorded during streamline gliding. Mean net force difference for each kick condition was then calculated.

Two-way repeated measures ANOVA was used to determine the effect of towing velocity and condition on net drag force (criterion measure). With significant ($p<0.05$) towing velocity / condition main effects and interaction evident, separate one-way ANOVAs were conducted on the towing conditions for each towing velocity. Post-hoc pairwise comparisons were performed following significant univariate one-way ANOVA results to determine towing condition the differences. Bonferroni adjustments for multiple comparisons and an alpha level of $p<0.05$ were used.

As a significant effect for dolphin kick was shown at all three towing velocities, further analyses were confined to this kick technique. Participants were ranked and divided into two groups (upper 50 % and lower 50 %) based on their dolphin kick raw drag force results for each of the three towing velocities. Separate independent groups t-tests were then performed between the upper and lower groups to determine if raw drag force significantly differed, at each towing velocity. Assumptions of normality and homogeneity of variance were screened using the Shapiro-Wilks and Levene's statistics. These assumptions were not violated.

The presence of significant upper and lower group differences in raw drag force prompted investigation of the possible contributions of anthropometric differences between groups. Separate pairwise comparison ANOVAs were performed on each anthropometric variable between the groups, for each of the three towing velocities. Type III sums of squares, Bonferroni adjustments for multiple comparisons and an alpha level of $p=0.05$ were used. With significant differences observed between groups on numerous anthropometric measures, particularly at the higher velocities, a Pearson product-moment correlation matrix was then constructed to identify relationships between all measured anthropometric variables, across all participants ($n = 18$).

Separate pairwise comparison ANCOVAs were performed on each kinematic variable between the groups, for each of the three towing velocities. Chest girth, body surface area and a slenderness index were run simultaneously in the analyses as covariates. Type III sums of squares, Bonferroni adjustments for multiple comparisons and an alpha level of $p=0.05$ were also used. To identify those kinematic variables that differed between the groups there was a need to account for differences in body dimensions between groups. The inappropriateness of including multiple, highly correlated variables as covariates in ANOCOVA (Tabachnick & Fidell, 1989) led to the inclusion of the three body form measures, representing the three forms of drag, as covariates in these analyses. This was performed to obtain clearer distinctions between dolphin kick technique kinematics, while controlling for differences in anthropometric dimensions between the groups. All statistical data analyses were conducted using an SPSS Statistical Analysis Package (version 11.5.1, 2002).

Results

The means and standard deviations for the net forces recorded at each velocity for the streamlined glide, flutter and dolphin kicking conditions are listed in Table 7.3. The net force difference between the prone streamlined glide and the flutter and dolphin kick conditions are listed in Table 7.4.

Table 7.3 Means (± SD) for the net force (N) recorded at each towing velocity and condition (n = 18)

Velocity	**Glide**	**Flutter**	**Dolphin**
1.9 $m.s^{-1}$	-82.64 ± 14.12	-67.04 ± 14.88	-56.18 ± 14.80
2.2 $m.s^{-1}$	-115.23 ± 17.30	-110.32 ± 21.11	-99.55 ± 22.07
2.5 $m.s^{-1}$	-143.02 ± 16.75	-143.68 ± 21.39	-132.27 ± 21.81

Table 7.4. Net force difference (N) between prone streamlined glide and the flutter and dolphin kick conditions (n = 18).

Velocity	**Flutter kick**	**Dolphin kick**
1.9 $m.s^{-1}$	15.59	26.46
2.2 $m.s^{-1}$	4.92	15.68
2.5 $m.s^{-1}$	-0.66	10.7

Results from the two-way repeated measures ANOVA revealed significant velocity-by-towing condition interactions [F (4, 68) = 8.05; p = 0.000]. Separate one-way ANOVAs conducted on each towing velocity revealed significant ($p<0.05$) differences between the towing conditions across all three towing velocities (see Table 7.5). At 1.9 $m.s^{-1}$ velocity towing, underwater dolphin kicking produced significantly less net towing force than the flutter kicking and streamlined glide conditions. This result indicates a clear advantage in using dolphin kicking compared to either flutter kicking or streamline gliding at this velocity. For the 2.2 $m.s^{-1}$ and 2.5 $m.s^{-1}$ velocities, flutter kicking net force was not significantly different from the streamlined glide condition, indicating no benefit to swimmers in flutter kicking at these velocities. Conversely, dolphin kicking net force remained significantly less than that produced during streamline gliding and flutter kicking while being towed at 2.2 $m.s^{-1}$ and 2.5 $m.s^{-1}$. This finding indicates a significant net drag reduction benefit to swimmers was obtained through dolphin kicking at these velocities.

Table 7.5. One-way ANOVA and pairwise comparison tests for the towing conditions at each separate towing velocity.

Velocity	**One-way ANOVA**			**Significant pairwise comparisons**
	F value	**df**	**p**	**(p<0.05)**
1.9 $m.s^{-1}$	46.399	2,34	0.000	Streamlined glide > flutter kick Streamlined glide > dolphin kick Flutter kick > dolphin kick
2.2 $m.s^{-1}$	18.398	2,34	0.000	Streamlined glide > dolphin kick Flutter kick > dolphin kick
2.2 $m.s^{-1}$	8.940	2,34	0.001	Streamlined glide > dolphin kick Flutter kick > dolphin kick

With a significant advantage demonstrated by dolphin kicking at all three towing velocities, further analyses were conducted on this kick technique in an attempt to identify critical features. Raw force was assumed to differ across each velocity due to the velocity drag relationship. Therefore, comparison between velocities was not performed. Participant classification of upper or lower 50 % of dolphin drag force was used again. Separate independent t-tests between the groups indicated significantly lower dolphin kicking raw drag forces for the upper 50 % group at all three towing velocities (see Table 7.6).

Table 7.6. Group means ± SD and independent t-test results between the upper 50% and lower 50 % raw drag force groups for each towing velocity.

			Independent t-test		
Velocity	**Group**	**Mean ± SD**	**t score**	**df**	**Sig. p**
$1.9\ m.s^{-1}$	Upper 50 %	-45.29 ± 8.55	4.636	16	0.000
	Lower 50 %	-67.07 ± 11.20			
$2.2\ m.s^{-1}$	Upper 50 %	-83.04 ± 10.29	4.821	16	0.000
	Lower 50 %	-116.06 ± 17.78			
$2.2\ m.s^{-1}$	Upper 50 %	-115.83 ± 9.50	4.913	16	0.000
	Lower 50 %	-148.71 ± 17.70			

Selected anthropometric measures were explored for differences between the groups. Significant differences were observed for numerous anthropometric measures when using separate pairwise comparison ANOVAs at the $2.2\ m.s^{-1}$ and $2.5\ m.s^{-1}$ velocities (see Table 7.7). A Pearson product-moment correlation matrix indicating those anthropometrical variables that shared significant common variance across all participants (n = 18) are included in Table 7.8.

Table 7.7. Anthropometric measures that varied significantly between the upper 50 % and lower 50 % groups, for each towing velocity.

Towing velocity (m.s^{-1})		
1.9	**2.2**	**2.5**
None	↓Height ↓Streamline height ↓Tib Lat to floor ↓Foot length ↓Foot width ↓Biacromial breadth	↓Mass ↓Height ↓Streamline height ↓Troch to Tib Lat ↓Tib Lat to floor ↓Biacromial breadth ↓Chest girth ↓Waist girth ↓Gluteal girth

Note 1. Troch = Trochanterion; Tib = Tibialis; Lat = Lateralis.

↓ Denotes the direction of the difference for the upper 50 % groups compared to the lower 50 % groups

With significant differences in anthropometric measures observed between the upper and lower groups (2.2 m.s^{-1} and 2.5 m.s^{-1} velocities) and the highly correlated relationships that exist between these measures, determination of the kinematic differences between groups is unlikely to be attributed to technique variation alone. The inappropriateness of including multiple, highly correlated variables as covariates in ANOCOVA (Tabachnick & Fidell, 1989) led to the calculation and inclusion of the three body form measures used by Lyttle et al. (2000) that represent the three forms of drag, as covariates in these analyses (chest girth: form drag; surface area: frictional drag; and slenderness index: wave drag). This was performed to obtain clearer distinction between dolphin kick technique kinematics, while controlling for differences in anthropometric dimensions between the upper and lower groups. Separate pairwise comparison ANOCOVAs were performed on each kinematic variable between the groups, for each of the three towing velocities. Type III sums of squares, Bonferroni adjustments for multiple comparisons and an alpha level of $p=0.05$ were used. The adjusted group Means (± SEM) for dolphin kicking kinematics measures are presented in Table 7.9. Adjusted Mean and percent differences between the groups' kinematic measures and significant pairwise ANOCOVA comparisons are listed in Table 7.10. Results indicated significantly larger vertical displacement of the hip measured in the upper 50 % group when towed at 1.9 $m.s^{-1}$ and 2.2 $m.s^{-1}$ (3.98 and 5.01 cm, respectively), and significantly larger vertical displacement of the knee at the 2.2 $m.s^{-1}$ (5.21 cm) tow velocity. Table 7.10 indicates that despite varying in magnitude, the differences in kinematic measures between the upper and lower 50 % groups all occurred in the same direction, but were non-significant.

Table 7.8. Pearson product-moment correlations for all anthropometric measures for all participants (n=18)

	Mass	**Height**	**Streamlined Height**	**Troch to Tibialis**	**Tibialis Lat to floor**	**Troch to floor**	**Foot length**	**Foot width**	**Biacromial breadth**	**A -P chest depth**	**Chest girth**	**Waist girth**	**Gluteal girth**	**Calf girth**
Mass (kg)	1	.691*	.620*	.379	.424	.426	.470*	.486*	.830*	.544*	.881*	.853*	.822*	.664*
Height (cm)		1	.965*	.841*	.829*	.886*	.571*	.575*	.657*	.483*	.513*	.513*	.430	.377
Streamlined Height (cm)			1	.840*	.913*	.930*	.583*	.582*	.573*	.404	.465	.500*	.363	.365
Troch to Tibialis lateralis (cm)				1	.778*	.943*	.360	.361	.457	.392	.239	.370	.091	.023
Tibialis lateralis to floor (cm)					1	.943*	.448	.443	.434	.175	.321	.419	.235	.277
Troch to floor (cm)						1	.428	.426	.473*	.300	.297	.418	.173	.159
Foot length (cm)							1	.999*	.446	.216	.404	.254	.311	.433
Foot width (cm)								1	.458	.220	.415	.267	.325	.444
Biacromial breadth (cm)									1	.569*	.780*	.791*	.645*	.394
A -P chest depth (cm)										1	.666*	.452	.400	-.102
Chest girth (cm)											1	.812*	.735*	.397
Waist girth (cm)												1	.752*	.494*
Gluteal girth (cm)													1	.708*
Calf girth (cm)														1

Note. Troch = Trochanterion; Lat = Lateralis; A – P = Anterior - Posterior

* Denotes significance ($p<0.05$)

Table 7.9. Adjusted Means (± SEM) for the upper (n=9) and lower 50 % group's (n=9) dolphin kicking kinematics measures.

	Velocity					
	1.9 m.s^{-1}		**2.2 m.s^{-1}**		**2.5 m.s^{-1}**	
Variable	**Upper 50 %**	**Lower 50 %**	**Upper 50 %**	**Lower 50 %**	**Upper 50 %**	**Lower 50 %**
Time per kick cycle (s)	0.461 ± 0.021	0.463 ± 0.021	0.456 ± 0.024	0.419 ± 0.024	0.438 ± 0.026	0.404 ± 0.026
Kick frequency (kicks.s^{-1})	2.190 ± 0.102	2.195 ± 0.102	2.204 ± 0.128	2.444 ± 0.128	2.324 ± 0.168	2.324 ± 0.168
Vertical displacement hip (cm)	11.90 ± 0.951	7.11 ± 0.951	11.16 ± 0.952	6.16 ± 0.952	10.16 ± 1.629	9.11 ± 1.629
Vertical displacement knee (cm)	24.59 ± 1.26	22.08 ± 1.26	25.75 ± 1.46	20.54 ± 1.46	23.81 ± 1.86	22.93 ± 1.86
Vertical displacement ankle (cm)	35.91 ± 2.09	33.73 ± 2.09	38.20 ± 2.19	31.59 ± 2.19	36.79 ± 2.69	33.23 ± 2.69
Vertical displacement foot (cm)	43.35 ± 2.25	45.21 ± 2.25	49.49 ± 2.45	41.72 ± 2.45	48.06 ± 3.33	43.10 ± 3.33
Knee range of movement (deg)	70.69 ± 2.76	70.00 ± 2.76	70.21 ± 3.01	65.83 ± 3.01	68.86 ± 2.17	60.97 ± 2.17
Ankle range of movement (deg)	36.35 ± 3.88	29.14 ± 3.88	29.51 ± 4.09	27.81 ± 4.09	29.09 ± 3.23	28.953 ± 3.23
Kick amplitude-rate ratio	103.29 ± 5.09	98.50 ± 5.09	109.30 ± 6.90	101.52 ± 6.90	109.99 ± 7.26	108.40 ± 7.26
Kick amplitude - streamline ratio	19.16 ± 0.92	18.43 ± 0.92	20.05 ± 1.01	16.98 ± 1.01	19.43 ± 1.36	17.56 ± 1.36

Table 7.10. Adjusted Mean and percent differences between the upper (n=9) and lower 50 % group's (n=9) kinematic measures with significant pairwise comparison ANOCOVA results.

	Velocity											
	1.9 m.s^{-1}				**2.2 m.s^{-1}**				**2.5 m.s^{-1}**			
Variable	**Diff.** ^{a}	**% Diff.** ^{b}	**Sig. p**	**95% CI**	**Diff.** ^{a}	**% Diff.** ^{b}	**Sig. p**	**95% CI**	**Diff.** ^{a}	**% Diff.** ^{b}	**Sig. p**	**95% CI**
Time per kick cycle (s)	-0.002	-0.4	0.944	±0.07	0.037	+8.8	0.331	±0.08	0.034	+8.4	0.428	±0.09
Kick frequency (kicks.s^{-1})	-0.005	-0.2	0.973	±0.32	-0.240	-9.8	0.248	±0.43	-0.210	-8.3	0.458	±0.60
Vertical displacement hip (cm)	3.98	+56.0	0.012*	±2.97	5.01	+81.3	0.005*	±3.20	1.06	+11.6	0.698	±5.75
Vertical displacement knee (cm)	2.51	+11.4	0.192	±3.94	5.21	+25.4	0.039*	±4.92	0.89	+3.7	0.777	±6.57
Vertical displacement ankle (cm)	2.18	+6.5	0.482	±6.51	6.61	+20.9	0.075	±7.39	3.56	+10.7	0.476	±10.48
Vertical displacement foot (cm)	2.14	+4.7	0.521	±7.02	7.78	+18.6	0.062	±8.23	4.96	+11.5	0.379	±11.76
Knee range of movement (deg)	0.69	+1.0	0.866	±8.62	4.39	+6.7	0.367	±10.14	7.89	+12.9	0.098	±9.58
Ankle range of movement (deg)	7.22	+24.8	0.220	±12.10	1.70	+6.1	0.794	±13.74	0.13	+0.5	0.980	±11.41
Kick amplitude-rate ratio	4.79	+4.9	0.526	±15.89	7.79	+7.7	0.481	±23.20	1.59	+1.5	0.895	±25.63
Kick amplitude - streamline ratio	0.73	+4.0	0.593	±2.87	3.07	+18.1	0.072	±3.39	1.87	+10.7	0.416	±4.81

Note 1. Diff. = difference between group means.

[a] Denotes difference in means following adjustment for the covariates. Calculated by subtracting the lower 50% group mean from the upper 50 % group mean.

[b] % difference = [(A - B)/B] x 100 where A and B represent the upper and lower 50 % group mean scores

Discussion

This investigation was limited to eighteen experienced male swimmers. Since Chapter 6 showed gender differences in factors affecting underwater dolphin kicking, the findings of this investigation are therefore limited to males and that any generalisation to female swimmers is both inappropriate and invalid. The primary aim of this investigation was to examine underwater kicking styles to enable greater understanding of technique and anthropometric characteristics that are predictive of efficient underwater kicking during freestyle turn wall exits. In part, this work augments the work of Lyttle et al. (2000) by including a kinematic analysis of underwater kicking techniques and examines underwater kick kinematics at velocities beyond those exhibited in free-swimming.

Lyttle (1999) stated that the preferred kicking resumption velocity following exit from the turn can be determined from towing testing by identifying the highest velocity at which kicking produces less net force than the streamlined glide position (cross-over velocity). In contrast to the findings of Lyttle et al. (2000), this investigation found a significant effect of underwater kicking style on net force. Results showed that underwater dolphin kick produced significantly less net drag force than the flutter kick and streamlined glide towing conditions across all three towing velocities. Subjects produced greater propulsive force without increased active drag. This finding indicates that for this population, underwater dolphin kick at these velocities is a superior kicking style and would prove advantageous when used following wall exit from a turn. In further contrast to the findings of Lyttle et al. (2000) a significant reduction in net force when dolphin kicking at the higher velocity of 2.5 m.s^{-1} (Lyttle et al., 2000: 1.9 m.s^{-1}

and 2.2 m.s^{-1} velocities only), indicated it was beneficial to dolphin kick rather than maintain a streamlined glide or flutter kick. As underwater kick proficiency increases, it is likely the cross-over point would occur at higher glide velocity (Lyttle, 1999). Therefore, this difference in findings is likely to be due to differences in underwater dolphin kicking proficiency between participants in each study. The increased proficiency in the present study may be, in part, due to a learning effect as several swimmers had prior experience at underwater kicking while towed. Nonetheless, this result highlights the need for re-evaluation of the velocity at which swimmers initiate underwater kicking without the detrimental effects of increased active drag.

No significant anthropometric difference was found between the upper and lower 50 % groups when towed at 1.9 m.s^{-1}. However, numerous significant anthropometric differences were observed between the upper and lower groups at the 2.2 m.s^{-1} and 2.5 m.s^{-1} velocities, indicating body dimensions may have influenced raw drag forces at these velocities. Several investigations (Chatard, Bourgoin et al., 1990; Chatard, Lavoie et al., 1990; Clarys, 1978a, 1978b & 1979; Ria et al., 1987; van Tilborgh et al., 1983) have demonstrated body cross-sectional area, height and weight to influence passive drag. Similarly, body cross-sectional area, mass, height, various body widths, lengths and circumferences have shown to be significantly correlated with active drag (Huijing et al., 1988). Despite research investigating the relationships between body dimensions and form with active and passive drag producing contrasting results, the present findings indicate smaller anthropometric dimensions to be consistent with decreased active drag during underwater dolphin kicking.

Although some studies suggest anthropometric parameters play a relatively minor role in active drag (Clarys, 1978a; 1979 & 1986; Toussaint et al., 1990), kinematic differences between the upper and lower groups are unlikely to be attributed to technique variation alone. The differences observed in so many anthropometric measures may be due, in part, to the presence of high inter-correlations between measures. This indicates these measures are highly representative of one-another and are therefore, easily reduced in number (covariates) for the purpose of group comparisons. When co-varying for body dimensions, significant kinematic differences were limited to increased vertical displacement of the hip in the upper 50 % groups when towed at 1.9 $m.s^{-1}$ and 2.2 $m.s^{-1}$ and significantly larger vertical displacement of the knee at 2.2 $m.s^{-1}$. This suggests that better dolphin kickers involve the hips and knees more than lesser kickers. One interpretation of this is that better dolphin performers start their dolphin movements with noticeable hip oscillations.

This result contrasts with the findings of the previous study in this series (Chapter 6) where vertical hip displacement was not highly correlated with underwater free-swimming dolphin kick velocity. Conversely, Shimonagata et al. (1997) and Arellano et al. (1998) reported whole body wave motions to be associated with skilled underwater dolphin kickers. In view of these contrasting findings, the relative importance of vertical hip displacement to underwater dolphin kicking remains unclear.

The lack of additional significant kinematic differences between the upper and lower groups could be due to the relatively small sample sizes and large performance variation. This is evidenced by the relatively high group mean difference 95 % Confidence Intervals, particularly at the 2.5 $m.s^{-1}$ towing velocity, thus indicating high variance in performance (see Table 7.10). This increase in performance variation is likely to have contributed to the contrasting, non-significant difference in vertical displacement of the hip between the upper and lower 50 % groups when towed at 2.5

$m.s^{-1}$. Although speculative, techniques containing larger vertical body movements and greater joint ranges of motion may have had a cumulative effect that contributed to the production of more efficient underwater dolphin kicking. For example, kick amplitude-rate ratios were 4.9, 7.7 and 1.5 % larger in the upper groups across the 1.9, 2.2 and 2.5 $m.s^{-1}$ towing velocities, respectively. This observation, in conjunction with greater vertical displacement of the foot (4.7, 18.6, and 11.5 % larger), implies these groups swam with larger kick size per time for each kick cycle than the lesser performed 50 % groups.

To produce larger kick sizes per time of each kick cycle, the upper group was likely to have produced faster, and therefore, more powerful muscle contractions through a greater range. Mookerjee et al. (1995) performed an investigation into leg strength and isolated swim kick performance. They found no significant correlation between isokinetic strength and surface flutter kicking times in female college swimmers. However, results from underwater film analysis on six participants led Mookerjee et al. (1995) to suggest that peak torque plays a significant role in surface flutter kicking performance. The relationships between strength, power and the subsequent torques at the knee with underwater dolphin kick velocity are unknown. However, these might prove to be important and warrant future investigation.

The present investigation did not find a significant relationship between ankle range of movement and increased underwater dolphin kicking efficiency. This is in agreement to the findings of the previous study (Chapter 6) and in contrast to the findings of several authors who report that increased ankle flexibility plays an important role in kicking speed (Barthels & Adrian, 1971; Cureton, 1930; Engesvik, 1992; Hull, 1990; Maglischo, 1993; Robertson, 1960; Ungerechts et al., 1998).

Mammalian dolphins are supreme exponents of undulatory swimming techniques. Despite anatomical differences between dolphins and humans, comparisons may bring about improved human swimming techniques. Dolphin tail beat amplitudes do not exceed values greater than 25 % of their body length (Ungerechts et al., 1998). The upper 50 % group of underwater dolphin kickers in the present study demonstrated kick amplitude – streamlined length ratios of 19.32, 19.99 and 19.02 % across the three towing velocities, respectively. Despite the upper 50 % group consistently demonstrating higher kick amplitude – streamline length ratios than the lower group, differences between the groups were not significant. This finding suggests no optimal relationship exists between kick amplitude and streamlined length in human underwater dolphin kicking. In contrast, Lyttle and Benjanuvatra (2004) postulated that smaller kicks while at higher velocities would be better due to less deviation from a streamline position and therefore less drag. The determination of optimal kick amplitude – streamline length ratios is of practical significance to the swimmer as optimal kick amplitude can be easily determined from measurement of streamline length. Therefore, additional empirical research is warranted to further explore the concept of optimal underwater dolphin kicking amplitudes.

Conclusion

The importance of selecting an appropriate underwater kicking technique and minimising the deceleration caused by drag following wall push-off from a turn has been stated frequently. The results of this study indicate that, for this population, underwater dolphin kick is a superior method of underwater swimming to that of flutter kicking at velocities ranging between 1.9 and 2.5 m.s^{-1}. A significant reduction in net drag force when dolphin kicking compared with streamline gliding shown at a towing velocity of 2.5 $m.s^{-1}$ indicates swimmers may initiate underwater kicking earlier than previously suggested following wall push-off from turns without detrimental increases in active drag. Smaller anthropometric body dimensions in this study were found to be consistent with decreased active drag during towed, underwater dolphin kicking. This was particularly so at the 2.2 and 2.5 $m.s^{-1}$ towing velocities. Trends in data also show larger vertical hip and knee movements are linked with more efficient underwater dolphin kick while being towed.

Chapter 8

Summary, Conclusions and Future Directions

Summary

Freestyle swimming turns can have significant bearing on overall swim performance. In recent years there has been an increase in the number of swimmers adopting a dolphin kick rather than the traditional flutter kicking wall exit in freestyle swimming turns. However, until now no studies have attempted to quantify the performance and hydrodynamic merit of each kicking technique. A series of studies were conducted to comparing dolphin and flutter kicking exits in freestyle turns to identify critical features of efficient underwater kicking technique.

The first study compared selected kinetic and kinematic variables recorded from freestyle turns that used dolphin and flutter kick exits performed by 20 male and 17 female age-group swimmers. Despite no difference being evident in wall approach velocities, contact and push-off forces between the turn methods, 5 m round trip time (RTT) was significantly slower for the dolphin trials. The fastest 33 % and slowest 33 % dolphin kick trials were compared in order to identify factors that contributed to the performance differences. Analysis of the data indicated faster RTTs were associated with, among other things, an increased kick frequency. This finding supports previous research that has shown higher kick frequencies in human underwater undulatory swimming (UUS) leads to increased swimming velocity (Arellano et al., 2000).

Poor dolphin kicking techniques demonstrated in the first study affected the ability to compare the merit of each wall exit strategy. Therefore, it was hypothesised that with increased practice at underwater dolphin kicking and dolphin kick turns, improved dolphin kick turn performances would enable a more appropriate comparison between the two turn styles. Hence, study two compared selected kinetic and kinematic variables recorded from freestyle turns that used dolphin and flutter kick exits, before and after six weeks of dolphin kick and dolphin kick turn practise. Attendance at training during the intervention period was poor with the mean number of trainings attended being 7.86 ± 3.24 from a possible 18 sessions. The consequence of such low attendance was that relatively little dolphin kick practice was performed by the group. However, despite this poor attendance, results demonstrated significant and equal improvements in dolphin and flutter kick turn 5 m RTTs. That turn RTTs were significantly improved with minimal practise is noteworthy and should be considered by coaches aiming to improve swimmer's race times. Despite significant improvement in both turn techniques, 5 m RTTs remained significantly slower for the dolphin trials compared with the flutter trials. That is, practice of dolphin kicking did not narrow the performance gap between flutter and dolphin turns in age-group swimmers.

Study three analysed the performances of eight male and five female experienced swimmers. It was believed that this swimming population would possess greater dolphin kicking experience and therefore, the ability to perform dolphin-kicking turn exits with greater consistency. In addition, assumed greater consistency in turn performance would allow differences in turn times to be more clearly attributed to turn style. Hence, it was proposed that this population would provide a more appropriate comparison of flutter and dolphin kick turns. Selected kinetic and kinematic variables recorded from freestyle turns using dolphin and flutter kick exits were again compared. Exits from turns that incorporated dolphin kicking were shown to be marginally, but not significantly, faster, for 5 m out-time compared to when a flutter kick wall exit strategy was used. However, the time spent kicking during dolphin trials was significantly greater than during the flutter kicking trials. Despite swimmers demonstrating large variation in dolphin kicking proficiency, this investigation showed dolphin kick wall exits produced equally fast 5 m-out turn times to flutter kick turn exits. A likely contributor to the varying dolphin and flutter kicking proficiency observed in study three was the variation in individual kicking technique. Conclusions regarding those technique parameters that contributed to proficient underwater dolphin or flutter kicking could not be clearly determined.

Study four sought to investigate the kinematic differences between free-swimming underwater flutter and dolphin kicking, and identify components of fast underwater kicking technique based on kinematic and anthropometric measures. Seventeen experienced swimmers (11 male and 6 female) were analysed when performing maximal effort natural dolphin, flutter and two modified dolphin underwater kicking swim trials. The free-swimming underwater dolphin kick technique was found to be significantly faster than that of the flutter and unpractised modified dolphin kicking techniques. Comparison between the three dolphin kick styles also highlighted that swimmers performed best at their usual technique. Regression analyses showed that to produce faster underwater free-swimming dolphin kick velocity, an optimal combination of greater foot width and greater vertical displacement of the ankle and foot is required. Gender differences were also observed in the factors that affected dolphin-kicking velocity.

Swimmer wall exit velocities following the turn in freestyle swimming are considerably higher than during maximal free-swimming. With free-swimming dolphin kicking shown to be significantly faster than flutter kicking for experienced swimmers, it was necessary to compare underwater kicking techniques at velocities higher than free swimming. Hence, study five explored underwater gliding and kicking kinetics and kinematics at velocities higher than underwater free-swimming. Eighteen experienced male swimmers were measured during prone streamline gliding, freestyle and dolphin kicking, while towed at three different velocities (1.9, 2.2 and 2.5 $m.s^{-1}$) at a depth of 0.5 m. Significantly lower net forces (propulsive force – drag force) were recorded during the dolphin kick trials across all three velocities. The results showed dolphin kicking rather than flutter kicking to be the superior kicking technique in this sample. When subjects were divided into upper and lower 50 % groups based on dolphin kicking performance, several anthropometric measures discriminated between the groups at higher than swimming velocities. At the 2.5 $m.s^{-1}$ towing velocities the upper 50 % group displayed significantly greater knee and hip vertical displacements. Similarly, significantly greater vertical hip displacements were displayed by the upper group at the 1.9 $m.s^{-1}$ towing velocities suggesting underwater dolphin kick actions incorporate the hips.

This thesis aimed to quantify the relative merit of performing traditional flutter and modified dolphin underwater kicking styles and their application to wall exists following the turn in freestyle swimming. For experienced and high calibre male swimmers, underwater dolphin kicking was found to be the superior kicking method during maximal free-swimming and during towing trials at velocities representing those experienced during freestyle turn wall exits. This finding confirms the growing trend in competitive swimming wherein a majority of swimmers employ this turn exit strategy during freestyle events. Although free-swimming and towed dolphin kicking was found to be superior to flutter kicking, this finding was not demonstrated during dolphin and flutter kicking freestyle turn performances. A variety of reasons for the majority of findings that did not support dolphin kicking out of freestyle turns as being beneficial were discussed.

Conclusions

This thesis investigated underwater dolphin and flutter kicking techniques and their application to exits following the turn in freestyle swimming. The main findings were as follows:

Study 1: Traditional and modified freestyle tumble turns by age-group swimmers

1. Using a kickboard, participants in the present study were able to kick on the surface in a prone position significantly faster over a distance of 25 m when using flutter kicking than dolphin kicking.

2. No difference existed between dolphin and flutter kicking turns for the approach to the wall, during wall contact and push-off, and to the resumption of kicking for age-group swimmers.

3. Freestyle turns that incorporate a dolphin kick wall exit produced significantly greater arm resumption distance and time, slower arm resumption velocity, greater surface distance and time than did flutter kicking turns.

4. Flutter kicking wall exits following the turn in freestyle produce significantly faster turn 5 m round trip times (RTTs) compared with a dolphin kick wall exit strategy for age-group swimmers.

5. Faster dolphin kick turns are indicated by greater peak horizontal wall force, faster wall exit, kick resumption and arm resumption velocities, smaller arm resumption time and shorter time spent dolphin kicking.

Study 2: Practice and performance of a modified freestyle tumble turn by age-group swimmers

6. For age-group swimmers, dolphin kicking and dolphin kicking turn practice produced significant and equal improvements in dolphin kick and flutter kick freestyle turn 5 m RTTs.

7. Flutter kicking remained the faster freestyle turn wall exit method, based on 5 m RTTs, following dolphin kicking and dolphin kicking turn practice.

Study 3: Traditional and modified freestyle tumble turns by skilled swimmers

8. For skilled swimmers, the use of dolphin or flutter kicking exits following freestyle turn wall push-off produced equally fast 5 m-out turn times.

a) No difference existed between dolphin and flutter kicking turns for the approach to the wall, during wall contact and push-off, and to the resumption of kicking for high calibre swimmers.

9. The time spent kicking during the dolphin trials was significantly greater and comprised 63.3 % of the time to 5 m-out compared with 45.6 % during the flutter trials.

10. Velocity above that of free-swimming was maintained for longer during the kicking phase of the dolphin trials.

Study 4: A comparison of lower extremity kinematics during free-swimming underwater kicking techniques

11. Free-swimming underwater dolphin kick was significantly faster than that of flutter kicking and two unpractised modified dolphin-kicking techniques, for this sample population.

12. Increased free-swimming underwater dolphin kick velocity is predicted to occur via an optimal combination of a greater foot width; increased ankle range of movement; and greater vertical displacement of the ankle and foot.

13. Gender differences were observed for factors that affect underwater dolphin kicking.

14. The superiority of unpractised modified (altered frequency and amplitude) dolphin kicking techniques to flutter kicking warrants their further investigation.

Study 5: A kinetic and kinematic analysis of underwater gliding and kicking

15. Experienced male swimmers demonstrated significant reduction in net drag force when dolphin kicking compared with streamlined gliding and flutter kicking at towing velocities of 1.9, 2.2 and 2.5 $m.s^{-1}$.

16. Swimmers were able to perform underwater kicking, without detrimental increases in active drag, earlier than previously reported.

17. Participants demonstrating greater underwater dolphin kick efficiency consistently performed with dolphin kick amplitudes representing 19% of total streamline length, when towed at velocities ranging between 1.9 and 2.5 $m.s^{-1}$.

18. Smaller anthropometric body dimensions were found to be associated with decreased active drag during towed, underwater dolphin kicking.

Appendix D: The use of subject derived scale factors for one-camera 2D analysis in underwater swimming.

19. Subject-derived calibration for one-camera 2D motion analysis demonstrated significantly smaller variation (error) than using a fixed reference calibration structure of known dimensions.

Future Directions

The following points represent general recommendations for future research.

1. Studies in this series compared biomechanical and performance characteristics of freestyle tumble turns using dolphin and flutter kicking exits in age-group swimmers. The superior flutter kicking ability demonstrated by participants, likely due to greater practice and more maturely developed movement patterns, contributed to superior flutter kick turn performance. In the likelihood that dolphin kicking may be an individually suited skill, further investigations into the comparison of proficient flutter and dolphin kick turn types in age-group swimmers should consider selection of participants with proficient kicking abilities. That is, attempts should be made to examine groups who demonstrate flutter and dolphin kicking proficiency.

2. Future turn intervention studies using age-group competitors should consider the learning and developmental rates of swimmers. Present findings demonstrated equal improvements in dolphin and flutter turn performance following increased dolphin turn practice. In addition, low participant numbers and poor attendance rates at trainings limited the findings. Further studies using age-group swimmers may consider incentives to increase training attendance, which may help to demonstrate greater intervention affects.

3. Alternatively, turn exit research could be focussed on swimmers who demonstrate more mature movement patterns where greater consistency in performance is attainable. This would enable intervention affects to be more clearly identified.

4. The use of 5 m out-time as the criterion measure for wall exit performance allowed better isolation of the underwater kicking component from the out-bound phase of the turn. Further studies into the kicking strategies used following turns should adopt this measurement criterion, as opposed to a 5 m RTT, to allow clearer comparison between wall exit kicking technique performances.

5. Regression analysis in Study 4 indicated a relationship between ankle range of movement and dolphin kicking velocity. An intervention study aimed at increasing ankle flexibility would serve to assess the practical significance increased ankle range of movement has on free-swimming underwater dolphin kicking velocity. Alternatively, a comparison study comprising participants selected on the basis of ankle ROM (good and poor) could further clarify the significance of ankle range of movement and dolphin kick velocity.

6. Comparison between the three dolphin kicking styles (natural, large and small) containing equal kick amplitude/rate ratios may reveal different results to the present findings. Collection of data allowing this comparison would require multiple swim trials from which an adequate number of performances containing equal kick amplitude/rate ratios could be identified. Despite obvious difficulties in obtaining an appropriate quantity of data, results would further highlight the importance of kick size relative to kick vertical leg movement velocity.

7. All participants in the present study performed underwater kicking with maximal effort and with no limitations placed on kick amplitude or frequency. Trends in results indicated consistent kick amplitude – streamline height ratios in the more efficient underwater dolphin kick groups at each towing velocity. Therefore, calculation of streamline height and kick amplitude in future studies could enable identification of optimal kick amplitude to body length ratio for human underwater dolphin kicking. However, because active drag increases with increased frontal area and increases with the square of the velocity, optimal kick amplitudes may vary depending on the velocity of movement. Hence, an ideal underwater kick strategy following the turn may incorporate small kicks, increasing in size; to an optimum based on an individual streamline length. To clarify if optimal kick amplitudes or frequencies exist, further studies should look at the effects of varying kick amplitude and frequency on net drag force while being towed at several velocities greater than free-swimming.

8. The present analysis methods could be used to examine underwater kicking techniques used following the turn in backstroke. In conjunction with establishing a drag profile, this analysis would allow efficient supine underwater kicking kinematics to be identified.

9. An inherent problem with swimming research is accessing sufficient participant numbers. The moderate subject number to variable ratios in the present work limits the application of findings to the general swimming population. Therefore, larger sample sizes of varying swimming experience levels and genders should be targeted in future work.

10. The kinematic analysis of underwater kicking techniques in the present works focussed on the lower extremity. With contrasting findings reported in the literature, anecdotally and within this work, the significance of upper body movements to underwater dolphin kicking efficiency remains unclear and warrants further investigation.

11. Data collection and treatment in the present investigation was limited to two-dimensional analyses. It is possible that the vertical oscillations of human legs during underwater dolphin kicking are not linear but include some curvilinear motion. Additional video cameras would facilitate a 3D representation of the legs during underwater kicking and should be considered for future research.

12. The relationships between leg strength and power with kicking efficiency were not explored in the present work. With increased kick amplitudes, higher kick frequency rates, smaller kick amplitude-rate ratios and greater kick amplitude-streamline rate ratios shown to be linked with greater dolphin kicking efficiency, the ability to produce fast leg kicking movements through greater range appears important. At present the relationship between underwater dolphin kick velocity and leg strength and power are not known and are worthy of investigation.

13. All investigations in this series focussed on the mechanics of underwater kicking techniques and turning. No attempt was made to quantify the energy costs relating to these techniques and within turn performance. Future attempts to optimise wall exits following the turn should also consider the physiological cost in conjunction with optimal underwater kicking technique and turn strategy. Similarly, if underwater kicking were maintained for greater distance following the turn, breath holding would be increased at greater physiological cost. Impending studies should investigate this concept.

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Appendix A: Publications from Doctoral Thesis.

Clothier, P. J., Payne, W. R., Harvey, J. T., Blanksby, B. A. & Benjanuvatra, N. (2004). The use of subject derived scale factors for one-camera 2D analysis in underwater swimming. *Journal of Human Movement Studies*, *46*(4), 333-345.

Clothier, P. J., McElroy, G. K., Blanksby, B. A. & Payne, W. R. (2000). A comparison and analysis of traditional and modified tumble turns by age-group swimmers. *Journal of Human Movement Studies*, *38*(2), 93-108.

Clothier, P. J., McElroy, G. K., Blanksby, B. A. & Payne, W. R. (2000) Traditional and modified exits following freestyle tumble turns by skilled swimmers. *South African Journal for Research in Sport, Physical Education and Recreation, 22*(1), 41-55.

Appendix B: Sample information, Consent and Medical forms.

UNIVERSITY OF BALLARAT

PLAIN LANGUAGE STATEMENT AND INFORMED CONSENT

PROJECT TITLE: Biomechanical analysis of a modified freestyle tumble turn.

INVESTIGATORS: Peter Clothier, Assoc. Prof. Warren Payne, Prof. Brian Blanksby.

PLAIN LANGUAGE STATEMENT:

The aim of the project is to determine how effective a modified freestyle tumble turn is compared to the traditional freestyle tumble turn. Is the modified turn faster? What type of swimmer is it faster for? How does the use of kicking effect deceleration following the turn?

As a participant you will be invited to perform pool related performance tests and have a number of body measures taken. These measures will include height, weight, limb lengths, girths, breadths, skin fold measurements and joint flexibility. Tests of leg and abdominal strength will also be required to be performed. The swim testing procedure will involve a warm-up followed by a series of 50m freestyle sprints in a 25m pool with an appropriate recovery period between efforts. Tumble turns at 25m will be performed on a force plate to measure wall forces during push off. A video camera will be positioned at right angles to record the swimmer from 10m into the wall and 10m out. Two 25m-kick time trials and a number of shorter (12m) underwater kicking sprints will also be performed and recorded using a hand held stopwatch and underwater videography.

You, the participant, will also be invited to perform tests while being towed underwater by a mechanical winch. Passive and active drag forces will be measured while being towed by the hands, along the length of a 25 m pool at a depth of 0.5 m underwater at each of three different velocities (1.9; 2.2; & 2.5 meters per second). At each velocity, the subjects will be required to perform a prone streamlined glide, prone freestyle kick and prone dolphin kick, with all kicks performed at maximal effort. Throughout the towing trials, a video camera will be positioned underwater and at right angles to the swimmer, and record the swimmer over a distance of 5 m.

Pool data collection will be carried out by Peter Clothier and Professor Brian Blanksby at the University of Western Australia. The land-based tests will be carried out at the University of Western Australia or a relevant swimming squad-training venue in Perth. For your benefit, the results of your performances will be kept with strict security by the researchers and may, given your consent, be forwarded to your coaches for feedback.

There are very few risks associated with participation in this study above the normal risks that would be encountered during training or competing. As a precaution, all participants will be screened via the use of a medical questionnaire (see attached). Previous research conducted by the investigators has shown very minimal risk to participants, with no instances of injury occurring during previous studies. Practice and familiarisation trials are included in every warm up prior to testing at race pace and all towing velocities as a safeguard to minimise any risk further.

I wish to thank you for consenting to participate in this study. Not only will your participation assist your performance as a swimmer but assist in developing current swimming techniques so we can achieve greater results.

Any questions you may have regarding your participation in this study can be can directed to Peter Clothier or Brian Blanksby at the school of School of Human Movement Studies, The University of Western Australia, Nedlands, on telephone number 9380 2658.

I (print name). . . . . of . . . . hereby consent to participate as a subject in the above research study.

The research program in which I am being asked to participate has been explained fully to me, verbally and in writing, and any matters on which I have sought information have been answered to my satisfaction.

I understand that

- all information I provide (including questionnaires) will be coded by number and stored separately from any listing that includes my name and address.
- aggregated results will be used for research purposes and may be reported in scientific and academic journals.
- my performance results throughout the study will be made available to my coach for analysis and myself from which feedback will be given.
- I am free to withdraw my consent at any time during the study in which event my participation in the research study will immediately cease and any information obtained from it will not be used.

SIGNATURE: . . . . DATE: . . . .

Parent or Guardians signature (for participants under the age of 18.)

SIGNATURE: . . . . DATE: . . . .

MEDICAL QUESTIONNAIRE

In order to participate in the battery of tests required for this research project, you are required to complete the following questionnaire.

Name: ________________________________.

Date: ______________.

Age: ________.

Please circle the correct answer to the following questions.

1. Do you smoke? Yes No

2. Has your family a history of cardiovascular problems (e.g. heart attack, stroke, etc.) Yes No

3. Do you suffer from any cardiovascular abnormalities (heart murmur, arrhythmic heart beat, etc?)

Yes No Don't know

If Yes, please state ____.

4. Are you a diabetic? Yes No

5. Have you suffered from any viral infections in the past month? Yes No

If Yes, please state ____.

6. Have you suffered from a cold in the past week? Yes No

7. Do you have high blood pressure? Yes No

8. Are you currently taking any medication? Yes No

If Yes, please state ____.

9. Are you suffering from any bone or muscle injuries? Yes No

If Yes, please detail ____.

10. Do you suffer from asthma? Yes No

11. Do you have any medical complaint, or any other reason which you know of, which you think may prevent you from participating in strenuous exercise? Yes No

If Yes, please state ____.

DECLARATION

I _____________________________ believe that the answers to these questions are true and correct.

Signed ________________________.

Date _____________.

Appendix C: Towing device description.

The following description is from the unpublished thesis titled "Hydrodynamics of the Human Body during the Freestyle Tumble Turn" by Andrew Lyttle, University of Western Australia, 1999. Full permission has been given by the original author to reproduce this work. Lyttle (1999) described the following:

Towing Device Description

A towing device was designed to measure above-water and underwater drag created by swimmers (see Figure 4.1). This towing device was used to quantify drag experienced at pre-determined velocities and depths. Essentially, a servo controlled mechanical winch was used to tow swimmers along the length of a 25 m pool. A pulley arrangement was positioned along the pool wall to enable the towing force to be essentially horizontal at the required depth. An underwater video camera monitored the trials to ensure the appropriate depth was maintained throughout the 12 m measuring range. The equipment used in the towing set-up is described below.

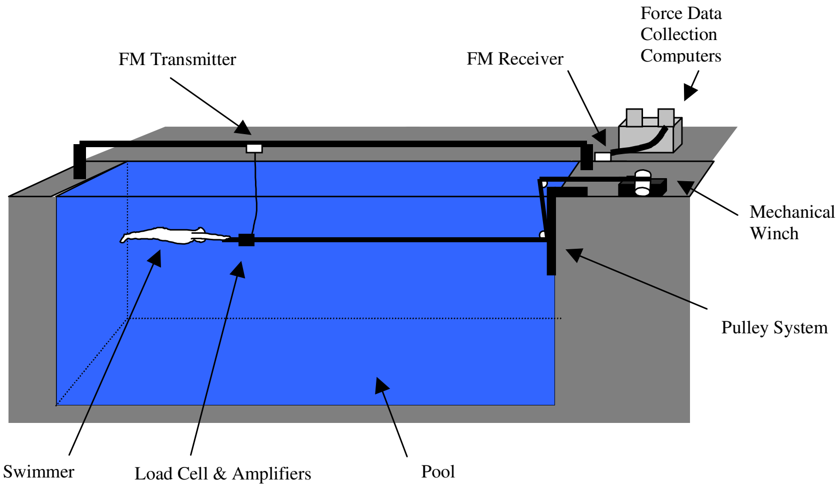

Figure 4.1. Experimental set-up for the collection of passive drag force recordings.

Mechanical Winch

A two horsepower, variable control, motorised winch (DC motor, Type RX70 MG7 D90L) with a gearbox ratio of 4.67, was used to tow the swimmers (see Figure 4.2). Stainless steel wire of 3 mm diameter was attached via a pulley system to the winch and the swimmer. This wound around a metal drum as the swimmer was towed through the water. A loop of nylon webbing was connected to the end of the wire and secured around the subject's wrists thereby preventing the webbing from sliding off the hands during towing. This allowed the swimmer to maintain a more streamlined position by overlapping the hands compared with the T bar grips and torso supports which were used previously (di Prampero *et al.*, 1974; Jiskoot & Clarys, 1975; Clarys, 1979).

Figure 4.2. Mechanical winch.

Velocity Control Unit

The towing velocity was determined via a variable control unit, which was attached to the motor and adjustable to 0.05 ms^{-1}. Pilot testing showed that this unit consistently controlled velocity between 1.6 and 3.1 ms^{-1} while towing different body types. High inter-trial reliability was found with the coefficient of variation for the velocity trials being 0.6% over 30 trials with three swimmers.

The motor was controlled remotely via a monitoring unit developed in the Department of Human Movement and Exercise Science at The University of Western Australia (UWA). This unit triggered data collection on the acquisition program, measured the displacement of the swimmer from which the velocity was calculated, and acted as a safety cut-off by ceasing the towing 5 m prior to the pool wall. Measurement of the displacement and calculation of the velocity of the swimmer was achieved by monitoring holes drilled at equal distances around the rim of the cylindrical metal drum. An optical electric sensor detected the holes as the drum rotated and produced a pulse train which represented the change in displacement over a given period. An instrument with an embedded controller (Type 8051) was then used to calculate and display the displacement, and the instantaneous and peak velocities. Following each towing trial, the times for each 2 m towing interval were displayed as well as the average velocity over the whole towing distance (15 m). When the wire was manually unwound over a measured 5 m distance, the error in the displacement measured by the unit due to rounding errors was less than 1%.

In addition to initiating towing, the velocity-monitoring unit triggered data collection after the swimmer was towed 3 m, and then discontinued towing after a further 12 m (total of 15 m). Pilot testing demonstrated that 3 m was sufficient distance to accelerate the swimmer to the required constant velocity over the velocity range used. Thus, drag could be recorded during the period of constant velocity only and not during the acceleration phase. The towing finished 5 m from the wall, which enabled the swimmers sufficient time to stop prior to reaching the end of the pool. A pre-loaded mechanical clutch (pre-load force = 350 N) was added as a back-up safety measure to disengage the motor in case of a failure in the electronic cut-off. A wire clamp was attached to the wire 3 m in front of the swimmer and, in the event of an electronic cut-off failure, the wire clamp would contact the pulley system on the pool wall with sufficient force to initiate clutch slippage and disengage the motor.

Data Acquisition

The drag forces resisting towing were recorded using a strain gauge, uni-axial load cell. The load cell employed four strain gauges (TML type: WFLA-6-1L) in a full Wheatstone bridge configuration mounted on a stainless steel cylinder (diameter – 0.07 m). Each strain gauge was encased within a transparent flexible epoxy resin and coated with a microcrystalline wax (M-coat W-1) for waterproofing. Vinyl leads from each strain gauge were attached directly to a waterproof PVC capsule (length - 0.25 m; diameter – 0.06 m) which contained the strain gauge amplifiers (see Figure 4.4). The size of the strain gauge cylinder and the waterproof capsule were positioned 0.4 m in front of the swimmer to reduce the effects of the flow disturbance. Calibration of the strain gauges was performed by suspending static weights from the cylinder and recording the strain gauge bridge output. Results of the calibration demonstrated a linear relationship ($R^2 = 1.00$) between the load applied and the voltage recorded (see Figure 4.3).

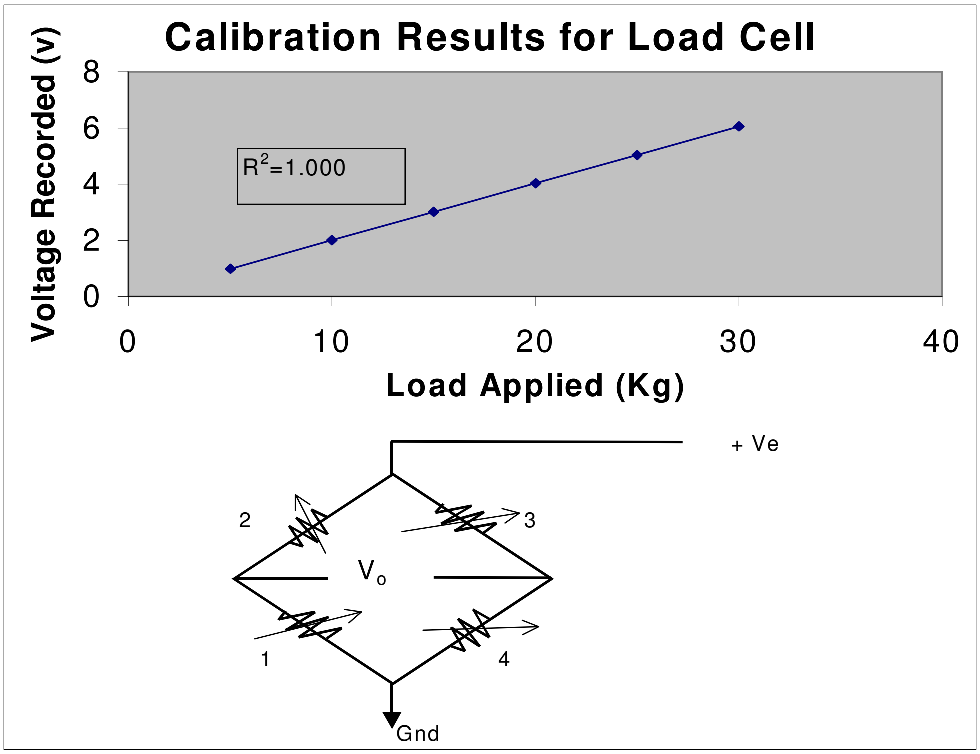

Figure 4.3. Load cell calibration and electronic schematics.

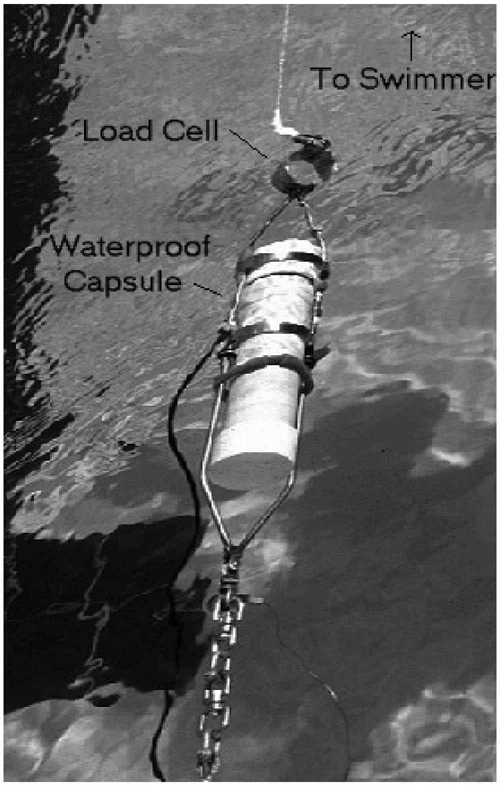

Figure 4.4. Image of the waterproof capsule and load cell.

Also housed within the waterproof capsule was a voltage-to-frequency converter that transformed the amplified strain gauge signal from a voltage to a frequency signal of 0 to 10 KHz. Both the strain gauge amplifier and voltage-to-frequency converter were designed and manufactured at UWA, and were powered via 9 v batteries. The frequency information from the load cell capsule was transferred via electrical cable to a Realistic FM modulator transmitter (carrier frequency of 36.7 MHz). The transmitter travelled along a roller system, above water, as the swimmer was towed. During pilot testing, attempts were made to transmit the FM signal using various frequencies from underwater. This was unsuccessful due to signal grounding problems from the chlorinated water environment and the plumbing used for heating the pool.

The FM data signals were received on the pool deck using a Realistic FM receiver/demodulator. The signals were then passed through a frequency-to-voltage converter where the frequency signals were transformed to a 0 to 5 volt reading with a gain setting of 50 N / 1 v. The voltage signals were collected at 200 Hz for 10 s on a PC computer using a PC-30, 12 bit A-D card, and processed using the AP30 force analysis program. The AP30 force data analysis program provides for real time data acquisition and analysis of analogue signals (Pearce, 1996).

Towing Depth Control

Depth was controlled using an adjustable, two-pulley system fixed to the pool wall (see Figures 4.5 & 4.6). The top, fixed pulley was attached to the main stainless steel tube. The lower pulley position was adjustable vertically along a track that reached from the water surface to 1.2 m deep, in 0.05 m increments. The lower pulley permitted the towing force vector to be horizontal at the required depth. (p. 90-94)

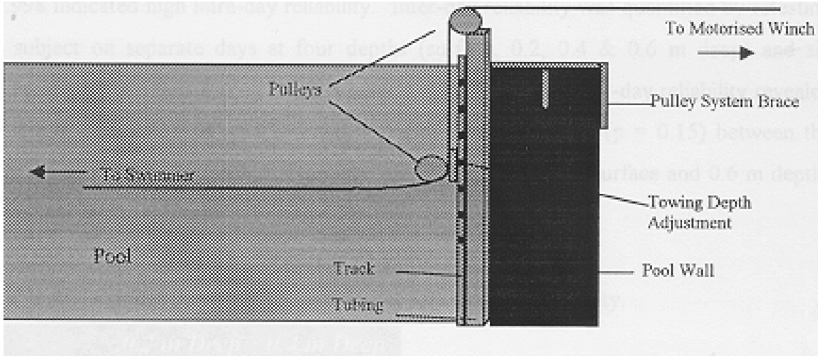

Figure 4.5. Schematic diagram of the pulley system for controlling depth.

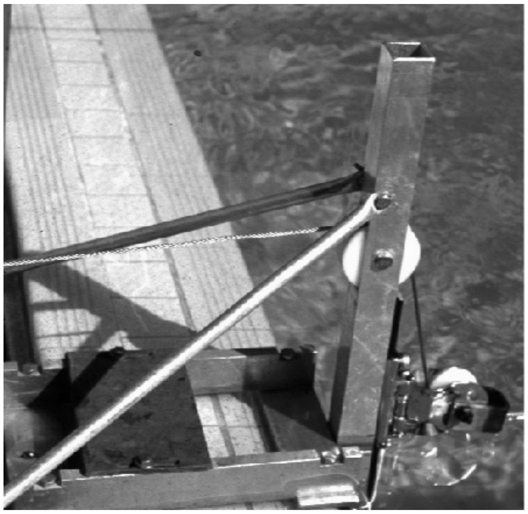

Figure 4.6. Pulley system for controlling depth.

Appendix D: Scale factor calibration study

A modified manuscript of:

Clothier, P. J., Payne, W. R., Harvey, J. T., Blanksby, B. A. & Benjanuvatra, N. (2004). The use of subject derived scale factors for one-camera 2D analysis in underwater swimming. *Journal of Human Movement Studies*, *46*(4), 333-345.

The use of subject derived scale factors for one-camera 2D analysis in underwater swimming.

SUMMARY

This technical note describes a comparison of relative errors in one-camera 2D underwater motion analysis when using two different control structure methods for calibrating video images. Eleven male and six female participants performed underwater kicking swim trials. A reference structure of known length and each swimmer's actual (land measured) thigh length were each used to calibrate the movement space from which digitised thigh lengths were calculated from each trial. For each trial, mean thigh lengths calculated using the two methods were then compared to actual thigh length for each swimmer and the differences recorded. Mean differences between actual and computed thigh lengths for the two methods were shown to be similar. However, the spread of mean differences was much less when the actual thigh length was used for calibration. This result strongly supports the use of thigh length as a more accurate method of calibration for one-camera 2D underwater motion analysis.

Introduction

The development of improved methods for quantifying spatial co-ordinates prior to motion analysis has enabled rapid expansion in knowledge pertaining to human movement. Abdel-Aziz and Karara (1971) developed the most commonly used technique for quantifying 3D co-ordinates - Direct Linear Transformation (DLT). The use of DLT in swimming studies is common practice (Berger, Hollander & de Groot, 1999; Cappaert, Pease & Troup, 1995; Payton & Bartlett, 1995; Payton, Baltzopoulos &

Bartlett, 2002; Yanai, Hay & Miller, 2000). Walton (1981) as cited in Kwon (1999) developed a variation of the DLT for 2D analysis involving eight parameters based on at least four control points. The 2D DLT method is especially applicable in underwater motion analysis (Kwon & Sung, 1995) as it allows greater freedom of camera placement (Kwon, 1999a). The ability to cover a wide object plane and the ability to place the optical axis of the camera other than perpendicular to the plane of motion are considered advantages of the 2D DLT method (Kwon, 1999a).

Despite being superseded by multiple camera analysis techniques (2D and 3D DLT), one-camera 2D analysis remains a critical tool for underwater motion analysis. Hay and Gerot (1991) explain that it is often not practical to use certain underwater filming techniques and equipment set-ups. Physical limitations such as access to, the location of underwater viewing windows, and the complications of using underwater housings can render 3D and 2D DLT methods of analysis expensive, extremely time consuming and difficult to perform.

Importantly, the method chosen for data collection must answer the pertinent questions about body motion (Plagenhoef, 1971). Movement such as underwater dolphin and flutter kicking predominantly involve motion in two dimensions, vertical and longitudinal. Hence, a one-camera 2D analysis system may be sufficient and more appropriate for measuring underwater kicking motions.

When limited to a one-camera data collection system, it is not possible to use DLT for spatial quantification. One-camera 2D analysis is dependent on the swimmer passing in a perpendicular plane of motion to the optical axis of the camera. A major concern when photographing human movement for analytical purposes is perspective error, a phenomenon fundamentally caused when one part of an object being filmed is closer to the camera than another part of that object. Hence, those parts closer to the camera appear larger than those further away. Cureton (1939) reported that perspective errors are greatly magnified when the camera is very close to the object being photographed or filmed. Therefore, camera positions placed further from the object being filmed can minimise perspective error (Cureton, 1939; Haven, Wilkerson & Bates, 1977). Ideally, a camera should be placed as far from the plane of motion as possible and zoomed in until the object fills the field of view (Peak Motus 32, 2001). However, pool dimensions and poor image quality associated with underwater videography often require swimmers to remain relatively close to the camera during filming. This positioning combined with the difficulty ensuring all swimmers remain the correct distance from the camera when free swimming, can potentially contribute to measurement error in 2D analysis. Variations in swim plane (closer to or further from the camera) relative to the position of a reference (calibration) structure are likely to increase perspective errors and subsequent errors of measurement.

Haven et al. (1977) stated that when the subject-to-camera distance varies, corrections should be made for perspective error by using a scaling factor for each subject to camera distance that occurs in the analysis. According to Haven et al. (1977), this process is relatively simple when exact subject-to-camera distances are known or the relative perpendicular distance from the camera can be determined because the subject touched the ground at some point during the analysis. The method developed by Haven et al. (1977) to calculate a scale factor for each performer relative to their position from the camera can not be applied in an aquatic environment, as at no time does a swimmer contact a fixed point at a known distance from the camera during free swimming.

The degree to which perspective error affects the accuracy of measurement in a one-camera 2D underwater swimming analysis system formed the basis of this investigation. Hence, the purpose of this investigation was to compare the relative error from one-camera 2D underwater motion analysis when using two different control structure methods.

Method

Sample

Data were collected from 11 male and 6 female participants who performed four maximum effort underwater kick swims using four different kick styles: flutter; natural dolphin; small dolphin; and large dolphin. These kick trials formed the basis of another study, and were used in the current study to investigate two separate methods of calibration. Ethics clearance and participant informed consent were obtained prior to the commencement of trials.

Data Collection

Prior to performing the trials, each participant was physically number-coded, and the hip, knee and ankle joint centres were highlighted with pen markings on the right side of the body, using procedures identified by Plagenhoef (1971). The right foot was also land marked at the distal head of the fifth metatarsal. The distance between the hip (trochanterion) and the knee (femur/tibia joint line) markings was measured twice and the mean recorded as thigh length (TEM = 0.11 cm). A Level Two trained anthropometrist performed all the land marking and measurement of thigh length. An example of participant land marking is presented in Figure 1.

Figure 1. A number coded participant with land markings.

Prior to the commencement of trials, a reference structure of known vertical and horizontal dimensions was positioned in the plane of motion, at a distance of 5.4 m perpendicular to the camera. Video images of this calibration structure were recorded prior to its removal, allowing the swim trials to begin. Data trials were conducted with participants assembling mid-pool (12.5 m from the pool wall) from where they were required, in order, to increase underwater kick velocity and have reached maximum velocity by the time they crossed a floor marker placed seven metres from the pool wall.

Maximum kick velocity was to be maintained from this point through to the end of the pool, during which time, lateral video images were recorded and stored for analysis. A departure time of 15 seconds was used between participants, who each repeated their four kick trials, with six minutes rest between trials.

Instrumentation

A Rosscraft Centurion anthropometry kit was used for the measurement of thigh length. Swim trials were captured at 50 Hz using a Panasonic MS5 S-VHS video camcorder. An exposure time of $500.s^{-1}$ was used and the video images were recorded on a Panasonic VCR (model AG-7350-E). The camera was positioned level and perpendicular to the field of view in an underwater viewing window 5.4 m lateral and perpendicular to the swimmer's path (plane), at a distance of 5.0 m from the end of the pool. This camera positioning was in accordance with the requirements for the traditional direct multiplier method of calibration (Peak Motus 32, 2001). The field of view was set to record the hip to foot complex over a minimum of two complete kick cycles.

Data analysis

When using a horizontal 2-point scaling device and the direct multiplier method of calibration, the generated horizontal scale factor is also applied in the vertical direction (Peak Motus 32, 2001). If the video monitor vertical and horizontal compression ratio is not 1:1, then error may be introduced in the vertical component. That is, the ratio between these two measures should be 1:1 if the picture is symmetrical and not compressed or extended vertically. To counter this potential error, measurement of the pixel to real world unit ratio was performed by separately digitising known lengths from a scaling device in the horizontal and vertical directions. Comparison of pixel to real world units was then made, allowing for adjustment in the vertical direction if necessary. No vertical picture compression or extension was found to be present in the system used to analyse the present data.

Calibration of the field of view was firstly performed using a Peak Motus 32 (version 6.1) motion analysis system and a horizontal reference structure of known length (2.8 m). Following this, the hip (trochanterion) and knee landmarks of a single leg were digitised over one complete kick cycle. A kick cycle was defined as the period in which the leg travelled through one complete up and down movement. Each complete kick cycle nearest to the centre of the digitising screen was chosen for analysis in an attempt to minimise refraction errors (Kwon, 1999b). Computed data were smoothed using a Butterworth filter with a Jackson-Knee optimal prescribed cut-off of 0.1 (Peak Motus 32, 2001). Mean hip to knee segment length calculated from the digitising process for one complete kick cycle was then recorded. An example of a digitised frame with segment overlay is presented in Figure 2.

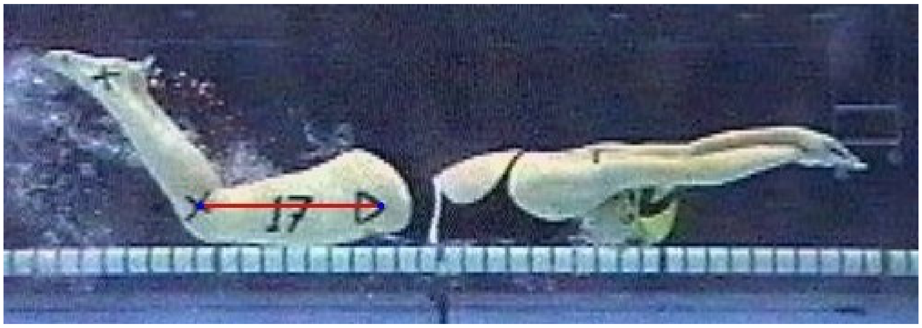

Figure 2. Swimmer with digitised trochanterion and knee landmarks, with segmental overlay.

Calibration of the field of view was then re-performed by digitising the mid-point of the knee and trochanterion landmarks and using the land measured thigh length as the known reference, for each swimmer in each trial. Care was taken during this process to ensure the thigh was horizontal and centred as near as possible in the field of view when digitised. Using the new calibration scale factor from each participant's trial thigh length, the original digitised data were re-smoothed using the same filtering algorithm. This process ensured no errors in calculation of predicted thigh length could be attributed to digitiser error or varying degrees of filtering. Mean hip to knee segment length (computed thigh) was then re-calculated from each complete kick cycle for this set of data and recorded.

Statistical analyses

Analysis in the present investigation was aimed at determining the relative accuracies of two methods of scaling, that is, to examine the discrepancies between the aquatic estimates of thigh lengths and the actual land measured thigh lengths, when using two different methods of calibration. The analysis is essentially an examination of measures of variability, including standard deviations (SD) and associated confidence intervals for the SDs.

Results

Mean land measured and computer calculated thigh lengths, and the difference between the two, are presented for each calibration method are presented in Table 1. Table 2. shows a number of measures indicating the spread in the two sets of data. Boxplots of the differences between land measured and thigh lengths estimated by the two methods are shown in Figure 3. Standard deviations of the difference between actual thigh length and the computed thigh lengths are shown in Table 3, together with confidence intervals for each SD based on the Chi Square distribution (see for example Wackerly, Mendenhall, & Scheaffer, 1996). The fact that the 99 % confidence intervals for SD using the two methods fail to overlap indicates that the observed difference between SDs is statistically significant at the 0.01 level.

Table 1. Mean thigh length and difference between land measured and computer calculated thigh length for each calibration method.

Calibration method	Mean land measured thigh length (cm)	Mean computer calculated thigh length (cm)	Mean Difference ± SD
Reference structure	44.63	45.40	-0.77 ± 3.23
Anthropometry	44.63	44.59	0.01 ± 0.24

n = 68

Table 2. Descriptive statistics for the difference between land measured and computer calculated thigh length for each calibration method.

Calibration method	n	SD	Min.	Max.	Range
Reference structure	68	3.23	-4.45	7.35	11.80
Anthropometry	68	0.24	-0.44	0.48	0.92

Table 3. Confidence intervals for the standard deviation difference between land measured and computer calculated thigh length

		Confidence interval for SD (99%)	
Calibration method	**SD**	**Lower**	**Upper**
Reference structure	3.23	2.59	4.02
Anthropometry	0.24	0.30	0.19

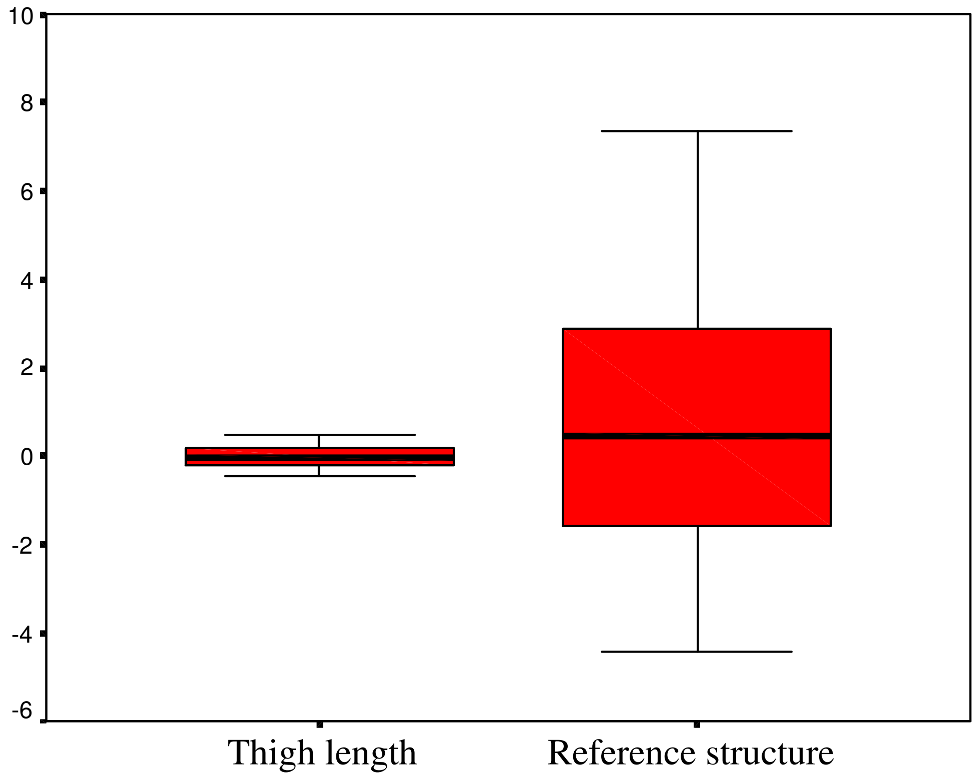

Figure 3. Boxplots showing the range of variation in the difference between land measured and computer calculated thigh length for each calibration method.

Discussion

A comparison of relative error from one-camera 2D underwater motion analysis when using two different control structure methods was performed. Mean scores for the two methods were shown to be similar, as was expected. However, the spread of mean differences were observed to differ substantially. Examination of the boxplots clearly illustrates the variances are vastly different for the two calibration methods. This result strongly vindicates the use of thigh length as a superior method of calibration for one-camera 2D underwater motion analysis.

Nonetheless, there are potential problems with this method. These limitations are largely related to extrapolation errors. Kwon (1999a) states you must not use a control object smaller than the movement volume to avoid large extrapolation error due to refraction. Hence, a potential limitation of using thigh length as a scaling device for one-camera 2D analysis is the length of the thigh itself. The potential for error being introduced through digitising is increased as the size of the scaling device is reduced. For example, if a scaling device is exactly ten pixels on the video monitor, but 11 pixels are digitised, then the systematic error introduced is about (11-10)/11 or nine percent. However, if the scaling rod covers 500 pixels on the video monitor, but the rod is mis-digitised by the same one pixel, the systematic error is (501-500)/501 or approximately 0.2 percent (Peak Motus 32, 2001). The magnitude of the error introduced may, however, be reduced by increasing the image size as this will result in a proportional reduction in the potential error caused through digitising, and is therefore recommended.

The longitudinal field of view required may also influence the appropriateness of using a one-camera 2D analysis system and subject derived calibration. The greater the longitudinal distance (wider field of view) over which the swimmer is required to be filmed, the smaller the thigh length will be relative to the image size on the screen and the number of pixels. This filming requirement potentially limits the use of this method of calibration to analyses comprising one, or at most two, complete swim stroke cycles. In most cases, this number of stroke cycles is adequate for technique analysis. Nonetheless, to ensure greater accuracy using this method, the object being filmed and the required movement volume should be maximised in the field of view.

For accurate thigh length calibration in one-camera 2D analysis, the pixel to real world unit ratio in the horizontal and vertical directions must be shown to be equal. If unequal, correction should be made. A system check can be performed by recording a scaling device of known horizontal and vertical lengths in the centre of the field of view to allow comparison of this horizontal – vertical aspect ratio. The distance this device should be placed from the camera is relatively independent of the performance trials, as the pixel to real world ratio should remain constant, irrespective of its initial image size.

Inherent problems associated with underwater filming have been recently been explored and documented by Kwon (1999a, 1999b). Unavoidable errors caused by the refraction of light through water, air and glass interfaces result in a "pincushion effect" distortion. Kwon (1999b) states that maximum errors occur at the outermost edges of the control volume space. Therefore, it is recommended that a control object be large enough to cover the entire space of motion in order to minimise coordinate extrapolation and subsequent inaccurate coordinate computation. Using subject-derived known lengths for calibration does not comply with this requirement and is therefore limited with respect to the recommendations of Kwon (1999b). However, the potential for perspective error as a result of swimmers travelling in a plane of motion nearer or further from the camera than a reference structure is considered far greater. For example, if a swimmer travels in a plane 20 cm closer to the camera over a distance of 5.40 m (the distance from lens to control structure in the present investigation set-up), the perspective error is equal to 0.2/5.40 m. This equates to a measurement error of 3.7 %. A 3.7 % error in the mean thigh length recorded in this investigation (44.63 cm) is equal to 1.65 cm. Maximising the size of the calibration object and using a camera lens with minimal fish-eye refraction will reduce pincushion effect distortion.

Conclusion

This investigation has shown that two different control structure methods produced vastly different variation in the prediction of known thigh lengths, when performing one-camera 2D underwater motion analysis. The use of actual land measured thigh length as a known calibration length was found to be far superior to use of a fixed reference structure. Subject-derived calibration for one-camera 2D motion analysis appears advantageous when relatively small longitudinal fields of view are required and the object to camera distance cannot be strictly controlled. Reductions in perspective error through using subject-derived calibration will allow greater accuracy in one-camera 2D swimming analysis

Appendix E: Raw, Summary and Statistical data

Information is contained within the CD located inside the back cover.