A THREE-DIMENSIONAL ANALYSIS OF INTRA-CYCLE KINEMATICS DURING 200m FREESTYLE SWIMMING

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Abstract

Purpose: The magnitude of maximum/minimum centre of mass (CM) velocity (V) and V fluctuation have been linked to freestyle swimming performance. Other kinematic parameters thought to be associated with performance are the body roll of the trunk and the maximum angular flexion of the elbow (MEF) and knee (MKF) joints. However, the uncertainty with respect to the accuracy of the methods for the calculation of the above parameters in the extant literature limits the value and generalisability of the reported data. Moreover, no studies have examined changes in these parameters across an event. Therefore, the main purpose of this study was to determine accurately, in three directions, the intracycle variations of the V of the CM during a 200 m maximum freestyle swim and to examine whether the V maxima/minima and the magnitude of V fluctuations are associated with performance. A second purpose of the study was to determine accurately the magnitude of shoulder and hip roll, MEF and MKF, and to assess whether these parameters are associated with performance. A third purpose was to assess whether the magnitude of bilateral asymmetries in each parameter is linked to performance.

Methods: Eleven male swimmers of national/international level performed a maximum 200 m freestyle swim in a 25 m indoors pool. Performance was recorded with four below and two above water synchronised cameras. A $6.75m^3$ purpose-built frame was used to calibrate the above and below water space. Anthropometric data were calculated with the use of the elliptical zone method. Four stroke cycles (SCs) were analysed for the 200 m (one for each 50 m). The following parameters were calculated: intracycle V of the CM for all directions, shoulder and hip roll, MEF and, MKF.

Results: Average V decreased as the swim progressed, with the exception of SC4 in which some swimmers maintained or increased V. Performance was strongly associated with maximum V throughout the swim, but was only associated with minimum V in SC3 and SC4. There was no association between performance and any other parameters. Large fluctuations in V were found in all directions, with the only significant change across the test recorded for horizontal V fluctuation which was higher in SC3 than in SC2 and SC4. This increase was mostly linked to a reduction in minimum V. The magnitude of V fluctuation was positively correlated with maximum V in most SCs. Swimmers rolled their shoulders considerably more than the hips, with shoulders and hips rolling towards the same direction during the SC. Hip roll increased and shoulder roll did not change during the swim. There were bilateral asymmetries in all parameters, with the magnitude of asymmetries not linked to performance. All swimmers had higher V during the right arm underwater phase (UWP) and rolled the shoulders more to the left (with one exception in each case showing overall symmetry). Maximum V occurred approximately at the same time as shoulder/hip roll maxima, while minimum V occurred at approximately the same time as MEF.

Discussion and conclusion: The ability of swimmers to achieve high maximum V seemed to be the main factor discriminating between faster and slower swimmers. High maximum V seemed to be associated with the generation of large resistive forces that possibly caused large reduction in the V of the faster swimmers at the early stages of the swim. However, the ability of faster swimmers to limit the decrease in V improved with each SC, with performance having a stronger correlation with the minimum than the maximum V in the last 50 m. The increase in horizontal V fluctuation in SC3 was associated with a reduction in V minima during UWP of the non-dominant arm. Swimmers should focus on the improvement of the effectiveness of the non-dominant arm, in order to establish symmetry in technique and improve performance. The decrease in the differences between shoulder and hip roll during the 200 m suggested that swimmers tended to adopt more hydrodynamic positions as the swim progressed. Analysis of intracycle V variations provided useful information for the balance between propulsive/resistive forces during a SC. In view of the results of this study, further understanding of freestyle swimming technique could be gained by examining parameters such as: orientation of the upper and lower extremities during the application of propulsive and resistive forces; relationships between performance and kinematic parameters for a larger range of velocities and analysis of net forces by examining intracycle accelerations of the CM.

Author Declaration

Edinburgh, September 2006

I hereby declare that:

a) I have composed this thesis,

b) This thesis includes my own work and,

c) This work has not been submitted for any other degree or professional qualification except as specified.

Stelios Psycharakis

Acknowledgments

Studying towards a PhD is more like an odyssey; a long journey that involves everyday battles against the Cyclops and Sirens of the challenging research world. The PhD, the academic Ithaca, is always there to motivate the scholar Odysseus.

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Table of Contents

List of Figures

List of Tables

List of Abbreviations

=	Equal
>	Greater than
≥	Greater than or equal to
<	Less than
≤	Less than or equal to
cm	Centimetres
kg	Kilograms
m	Metres
mm	Millimetres
sec	Second
2D	Two-dimensional
3D	Three-dimensional
ANOVA	Analysis of variance
APAS	Ariel performance analysis system
CM	Centre of mass
DLT	Direct linear transformation
eZone	PC version of the elliptical zone method (Deffeyes & Sanders, 2005)
MEF	Maximum elbow flexion
MKF	Maximum knee flexion
p	Probability level (α)
r	Pearson's product moment correlation coefficient
ROM	Range of motion
SC	Stroke cycle
SD	Standard deviation
SL	Stroke length
SPSS	Statistical package for social sciences
SR	Stroke rate
UWP	Under water phase
V	Velocity

1. Introduction

The introduction is presented in two sections. The first section refers to the intracycle velocity of the centre of mass (CM) of a swimmer. The second refers the kinematic parameters that are related to the intracycle velocity of the CM of the swimmer.

1.1 Intracycle velocity

The amplitude of velocity (V) variation of the CM during certain phases of the swimming stroke cycle (SC) has been linked to swimming performance (e.g. Takagi *et al.*, 2004). Togashi & Nomura (1992) stated that faster swimmers have lower V fluctuations than slower swimmers. Cappaert *et al.* (1995) suggested that elite swimmers minimise the reduction in V caused by resistive forces during the decelerating phases of a stroke. The calculation of intracycle horizontal V variation would enable the determination of the extent to which different phases of the SC are propulsive and improve the understanding of swimming technique.

For the aforementioned reasons, researchers have studied the intracycle horizontal V fluctuations of swimmers during freestyle (e.g. Maglischo *et al.*, 1989; Keskinen & Keskinen, 1997), backstroke (Maglischo *et al.*, 1989), butterfly (e.g. Sanders, 1996b; Barbosa *et al.*, 2003) and breaststroke swimming (e.g. Colman *et al.*, 1998; D'Acquisto & Costill, 1998). There was a general agreement that swimming V constantly changes during a SC for all four swimming strokes, with marked periods of acceleration and deceleration identified in some strokes. Comparative data between faster and slower swimmers have not been adequately reported, especially for freestyle and backstroke. However, some studies in butterfly and breaststroke showed that faster swimmers have higher V maxima/minima and lower V fluctuations than slower swimmers (e.g. Maglischo *et al.*, 1989; Togashi & Nomura, 1992; Sanders, 1996b; D'Acquisto & Costill, 1998; Takagi *et al.*, 2004).

Limitations in the studies conducted in this area reduce the validity and do not allow generalisation of the reported data. One of the major limitations is associated with the V calculation methods. Horizontal swimming V has been measured as the V of either a fixed point on a swimmer's body (such as the hip) or the CM. However, the motion of the hip joint is also dependent on an individual's differing trunk rotations, and inertial effects created by forward or backward leg or arm movements, even when no propulsion or resistance is generated (Colman *et al.*, 1998). Additionally, Barbosa *et al.* (2003) reported that the hip did not represent accurately the intracycle behaviour of the kinematic variables of the CM in butterfly swimmers, as the former presented a higher intracycle variation than the latter, with weak correlations between the values obtained from the two calculation methods.

Furthermore, there have been very few studies of the V of the CM in which three dimensional (3D) methods have been used. In the vast majority of studies, two dimensional (2D) data were collected on one side of the body and bilateral symmetry was assumed. However, recent studies have revealed technique asymmetries and lateral dominance in V patterns (e.g. Keskinen & Keskinen, 1997; Tomkinson & Olds, 2000; Arellano *et al.*, 2003).

In addition to the limitations described above, there is a plethora of parameters that still remain to be investigated in this area. For example, researchers have examined just the horizontal component of V. Consequently, there is no information about the V fluctuations in the vertical and lateral directions, and their association with performance. Another area to be investigated is the V changes occurring between different SCs across the course of a race, since all existing studies have limited their analysis to V fluctuations for one SC. Research conducted during incremental tests (e.g. Keskinen & Komi, 1993; Psycharakis *et al.*, 2002) and throughout competitive swimming events (e.g. Chatard *et al.*, 2001a; 2001b; 2001c) has shown that basic kinematic parameters, such as stroke rate (SR) and stroke length (SL), change with V throughout an event. Thus, the intracycle V pattern of the CM may also change. Investigation of changes in intracycle V during an event would further improve the understanding of swimming technique.

As discussed above, knowledge of more specific changes within the SCs in all three directions remains limited. Further, the uncertainty with respect to the accuracy of the methods of calculating intracycle V in the extant literature limit the value and generalisability of the reported data. Therefore, there is a need to assess accurately the 3D intracycle V pattern of the CM in three directions. This would facilitate the assessment of the extent to which intracycle V fluctuations and V maxima/minima are associated with swimming performance. Calculation of intracycle V throughout a swimming event would provide useful information regarding the magnitude of possible variations and the association with the performance level of the swimmers. Such information can be used as a guide to swimmers, coaches and researchers, for the purpose of identifying/correcting errors and improving swimming performance.

1.2 Other kinematic parameters related to velocity

1.2.1 Kinematic parameters of the trunk

Given that freestyle horizontal swimming V changes constantly during a SC, it is expected that other kinematic parameters related to a swimmer's body position in the water would also change. Researchers have studied intracycle changes in various kinematic parameters related to the motion of the trunk and the upper and lower extremities. For example, Cappaert *et al.* (1995) reported that body roll of the trunk and the maximum flexion angles of the elbow and the knee are associated with changes in V.

Body roll, defined as the rolling action of the trunk around its longitudinal axis, appears to have important functions in freestyle swimming and to be linked to swimming performance. It has been suggested that body roll facilitates the breathing action (Yanai, 2001), reduces the risk of developing shoulder injuries (Ciullo & Stevens, 1989), and influences the hand displacement relative to the water thereby contributing to the hand V (Payton *et al.*, 2002). In view of the possibility that body roll may play an important role in improving swimming performance, some investigators have tried to determine the effect of body roll on freestyle kinematics with the use of computer simulation models (Hay *et al.*, 1993; Payton & Mullineaux, 1996; Payton *et al.*, 1997), or during experimental studies (Liu *et al.*, 1993; 1999a; Payton *et al.*, 1999b; Yanai, 2001; Castro *et al.*, 2003; Yanai, 2003) and competition analyses (Cappaert *et al.*, 1995; 1996; Cappaert, 1999).

The models used in computer simulation studies showed that body roll influences hand V and displacement in various ways. However, the validity of these models has not been established and, additionally, some of the assumptions made in these studies were proved to be incorrect by later investigations. For example, Payton *et al.* (2002) indicated that the investigators in the computer simulation studies assumed incorrectly that the trunk rolls away from the neutral position and that the arm rotates laterally relative to the rolling trunk for the duration of the insweep.

Most studies conducted during swimming tests showed that body roll influences the V and displacement values in freestyle (Liu *et al.*, 1993; Payton *et al.*, 1999a; 1999b; Yanai, 2001). It was reported that the body roll angles of competitive swimmers decreased with increasing V and also that swimmers rolled less to the non breathing side than the breathing side. However, except the studies of Yanai (2001; 2003), body roll in these studies was measured for the whole trunk, by attaching a wooden fin on swimmers' backs and calculating its deviation from the vertical axis. Cappaert *et al.* (1995), proved that the assumption that the whole trunk rolled as a rigid segment is not tenable because the shoulders and hips roll to different extents and in some cases with different phase. Thus, body roll needs to be re-examined with methods that do not rely on that assumption.

The analyses by Cappaert *et al.* (1995; 1996) using video data obtained from swimmers during competition and Yanai's studies (2001; 2003) on university swimmers, appear to have been the only studies conducted in 3D and to quantify separately the shoulder and hip roll of swimmers. Cappaert *et al.* indicated that elite swimmers rolled the shoulders and hips in phase, that is, both moving in the same direction at the same time despite having differing magnitudes of roll. Subelite swimmers, on the other hand, appeared to have similar ranges of shoulder and hip roll to elite swimmers but the hip and shoulder roll were not in phase. Cappaert *et al.* stated that the opposite roll between the shoulders and the hips of the subelite group might have increased active drag by increasing frontal surface area. Cappaert (1999) also reported that sprint freestyle swimmers (200 m and below) have less shoulder roll during certain phases of the SC than distance freestyle swimmers (above 200 m). The competition analyses implied that faster swimmers use body roll more effectively than slower swimmers (reducing the active drag and therefore improving performance) and that body roll might be related to freestyle swimming V. Yanai (2001), although focusing on kinetic parameters, reported nearly equal phase angles but different magnitudes of shoulder and hip roll among university swimmers.

Finally, Yanai (2003) reported that shoulder roll decreased when swimming V increased.

While the above studies provided some useful data on body roll, more research must be conducted. Improved methods are required to reduce errors associated with: not considering the influence of breathing actions; extrapolating beyond small calibration volumes; reduced reliability of digitising due to a limited number of cameras; adjustments made for combining above and below water data and; image distortion and refraction. Moreover, there remains a lack of information regarding bilateral asymmetries in the magnitude of roll and their association with performance. Further, these studies were limited to the analysis of one SC. Therefore changes that occur in shoulder/hip roll throughout the course of a race and the relationship of these changes to performance remain unknown.

1.2.2 Kinematic parameters of the upper and lower extremity

There are only a few studies of the changes in kinematic parameters related to the motion of upper and lower extremities, with the majority being of the freestyle stroke. The main kinematic parameters that have been reported to affect V (and, therefore, swimming performance) are the magnitude of maximum angular flexion of the elbow (e.g. Cappaert *et al.*, 1995; Cappaert, 1999; Duclos *et al.*, 2003) and the knee (e.g. Sheeran, 1978; 1980; Cappaert *et al.*, 1995; Cappaert, 1999).

Cappaert *et al.* (1995) reported that elite swimmers had significantly larger values ($p<.05$) than subelite swimmers for angles of maximum elbow flexion (MEF) during the underwater phase (UWP) of the stroke. Duclos *et al.* (2003), following an analysis of some parts of the SC, reported that elite swimmers had greater angular range of motion (ROM) at the elbow than subelite swimmers..

Only a few other upper extremity kinematic parameters, such as the maximum vertical displacements of the elbow and wrist, have been examined in relation to freestyle swimming V. These parameters, however, have not been found to be directly associated with changes in V. For example, Cappaert *et al.* (1995) after normalising the values according to anthropometric characteristics, found no differences between elite and subelite swimmers for the underwater stroke depth (vertical wrist and elbow displacement).

However, the elbow angle/time patterns have not been adequately studied, particularly with respect to changes across a race distance. In addition, methodological limitations have reduced the accuracy and reliability of the reported data. These limitations have arisen from: insufficient number of cameras used; lack of calibration procedures and methods' reliability/error assessment and; inadequate statistical analysis and reporting. Further, no researchers have attempted to quantify bilateral asymmetries in MEF and their association with performance.

The angle of maximum knee flexion (MKF) is the only lower extremity kinematic parameter that has been found to be related to swimming performance. Cappaert (1999) found that elite and sprint swimmers have higher MKF than subelite and distance swimmers, respectively. A larger MKF appears to be beneficial as it gives the foot a larger ROM to produce propulsive forces. However, similar to the studies of upper extremity parameters, these studies were limited by the methods used. In addition to the methodological limitations, there is a lack of data regarding bilateral differences in MKF and changes in MKF values throughout the course of an event.

1.3 Purpose of the study

The main purpose of the study was to determine accurately, in three directions, the intracycle variations of the V of the CM in male freestyle swimmers, throughout a 200 m maximum swim. Moreover, to examine if the V maxima/minima and the magnitude of V fluctuations are associated with performance (as indicated by average horizontal V). A second purpose of the study was to determine accurately the magnitude of shoulder and hip roll and maximum elbow and knee flexion, and to assess whether these parameters are associated with average swimming V. A third purpose was to calculate bilateral asymmetries in all parameters, and to identify if the magnitude of bilateral asymmetries is associated with performance.

2. Literature Review

This thesis focuses on the kinematics of competitive swimming. Therefore, literature was reviewed to explore the existing scientific knowledge and to identify any gaps and/or limitations in this area. The review is presented in three sections: the first section briefly introduces research on the generic kinematic parameters that describe performance (SR, SL and average swimming V); the second section presents studies on the main kinematic parameter of interest with regard to swimming V, the intracycle V fluctuations; the third section refers to other kinematic parameters related to the motion of the trunk, and upper and lower extremities that have been found to be associated with V and/or performance.

2.1 Average swimming velocity, stroke rate and stroke length

Swimming V has been defined as the product of SR and SL (Craig *et al.*, 1985). SR (cycles/min) refers to the number of complete cycles of one arm in a minute (or any other given unit of time), while SL (m/cycle) is the distance the swimmer moves forward per stroke cycle (SC) (Keskinen & Komi, 1988). However the definition is valid only for mid-pool swimming V, since the average V of a swimming event is influenced by other factors, such as the time spent during starts and turns.

As SR and SL are kinematic parameters related directly to swimming performance, several authors have underlined their importance in swimming training (e.g. Maglischo, 1993; Thompson *et al.*, 2000). Furthermore, these parameters have been the subject of numerous studies. Researchers have studied the variations in SR and SL according to:

- Increasing V (e.g. Craig & Pendergast, 1979; Keskinen & Komi, 1988; Weiss et al., 1988; Keskinen & Komi, 1993; Psycharakis et al., 2002).
- Anthropometric characteristics (e.g. Grimston & Hay, 1986; Kennedy *et al.*, 1990; Chengalur & Brown, 1992; Pelayo *et al.*, 1996).

- Different swimming strokes (e.g. Pai *et al.*, 1984; Kennedy *et al.*, 1990; Chengalur & Brown, 1992).
- Race distance (e.g. Craig *et al.*, 1985; Kennedy *et al.*, 1990; Chengalur & Brown, 1992; Arellano *et al.*, 1994; Pelayo *et al.*, 1996).
- Progress of an event (throughout the course of the race) (e.g. Letzelter & Freitag, 1983; Sidney *et al.*, 1999; Chatard *et al.*, 2001a; 2001b; 2001c; 2001d).

The main research findings in this area could be summarised as follows:

- The SR and SL combination for achieving a given V varies between and within swimmers.
- Swimmers generally increase V by increasing SR and decreasing SL, regardless of the stroke, age or sex of the swimmers. Due to the reduced time of the SC when stroke frequency increases, SL decreases.
- Faster swimmers have generally longer SL and similar SR to slower swimmers.
- Different combinations of SR and SL have been shown to be equally successful during 200 m events.
- As the event distance increases SR and V decrease, while SL increases with increasing race distance up to 200 m and decreases from 200m as race distance increases.

Competition data regarding SR, SL and average V are often available on the internet following the end of a competition (e.g. Haljand, 2006). Nevertheless, such analyses are generally limited to reporting the values for these parameters, without describing and/or assessing the accuracy and reliability of the methods used. Moreover, no further analysis or evaluation of the reported data is usually attempted. Therefore, despite the considerable number of investigations carried out in this area, the SR, SL and average V relationships have not been sufficiently studied (in the form of published scientific papers) for all strokes and distances. For example, there is a lack of data for 50 m events (other than freestyle), for 800 m and 1500 m freestyle events, as well as for within event differences (with the exception of 200 m events). Furthermore, several limitations exist in the conducted studies. First, many studies have limited the analysis to just one SC, therefore restricting the reliability and ability to generalise the results. Second, the method and test designs used in experimental studies have been limited and are thereby unlikely to provide such information that would be applicable to swimmers of most strokes and distances. Another major limitation has been the methods employed for calculation of kinematic parameters, such as: calculation of V by dividing the distance swam by the time spent; calculation of SR with the use of stopwatches and calculation of SL by dividing the distance swam by the number of SCs measured for that distance (details regarding methods employed for the calculation of stroke parameters by the studies discussed in this section are shown in Table A.1, Appendix A). As shown by Chollet and Pelayo (1999), different methods of calculation produce different errors in measurements, the magnitude of which depend on various factors such as inter- and intra-operator reliability, stroke and distance of the swimming test. Considering that researchers have used several methods for the calculation of kinematic parameters without, in many cases, providing any error estimates or correction factors, any data generalisation or between studies comparisons are limited by the accuracy and reliability of the reported data.

In addition to the limitations described above, the vast majority of the studies discussed in this section have used 2D approaches with a single camera. However, such approaches restrict the calculation of other variables that might be more beneficial to elite swimmers. For example, Sanders (1999) stated that the measurement of SR and SL might be informative with respect to performance and performance potential, but limited with respect to providing a better understanding of the efficiency of the swimming technique, identifying factors that influence swimming performance and developing strategies for improving the performance of individual swimmers.

2.2 Intracycle velocity

Increasing recognition of the limitations of quantifying only race parameters such as SR and SL has led to the evolution of biomechanical equipment and analysis methods, and more frequent quantification of other kinematic parameters related to swimming performance. The intracycle V of swimmers has been one of the main kinematic parameters of interest. Intracycle V is directly related to swimming performance and its analysis could provide valuable information for swimmers and coaches, and a better understanding of swimming technique. For example, Maglischo *et al.* (1989) stated that the measurement of horizontal V throughout a SC is of great value because changes reflect differences between the propulsive and resistive forces. Togashi & Nomura (1992) stated that faster swimmers have lower V fluctuations than slower swimmers. These investigators claimed that a large fluctuation in horizontal V causes a swimmer to use a greater amount of energy for propulsion and is, therefore, inefficient. D'Acquisto and Costill (1998) reported that faster swimmers are characterised by higher maximum and minimum intracycle velocities than slower swimmers.

For the purpose of detecting more specific V changes within a SC and assessing the causes and effects of these changes, many research teams have studied the intracycle variation of swimmers' velocities in all four strokes. The following two sections present the general intracycle V patterns and the magnitude of intracycle V fluctuations in all strokes. The limitations associated with the methods used for data collection and analysis, as well as the identified gaps in this area are presented in sections 2.2.3 and 2.2.4.

Finally, precise analysis of kinematic parameters of the CM requires accurate anthropometric data, such as the mass, volume and CM location of individual body segments and the whole body. As these parameters cannot be measured directly for living subjects, a method that estimates these parameters must be employed. Considering that the accurate analysis of CM V fluctuations was one of the main purposes of this study, section 2.2.5 reviews the anthropometric measurement methods for estimation of a body's CM.

2.2.1 Velocity patterns

There are only two studies that have described the intracycle V variations in freestyle swimming. Maglischo *et al.* (1989) tested 18 male and female Olympic level swimmers who were swimming at maximum speed. The investigators identified marked periods of acceleration and deceleration within each SC. Swimmers had V patterns with two distinct maxima, even though other V maxima -smaller in magnitude- existed in some swimmers' patterns. However, the illuminating work of Maglischo *et al.* on the patterns of all four competitive strokes limited the analysis to qualitative evaluation of the graphs presented for some swimmers, without attempting any quantitative analysis. Figure 2.1 shows the V patterns presented in this manuscript for two freestyle swimmers.

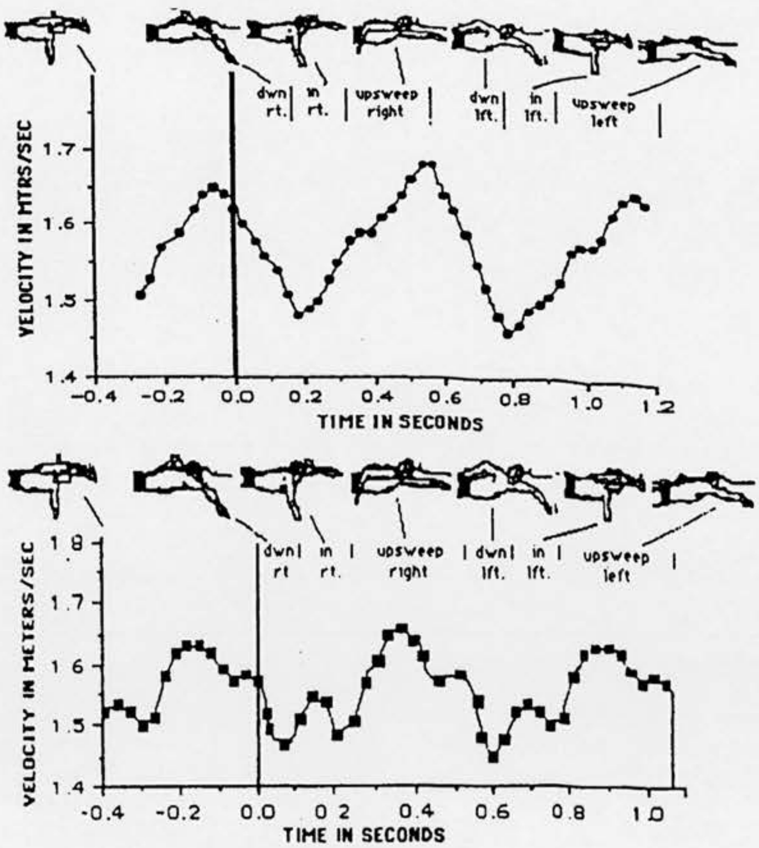

Figure 2.1: Horizontal V patterns for two freestyle swimmers
(Adapted from: Maglischo *et al.*, 1989)

In the only other study conducted in freestyle, Keskinen and Keskinen (1997) examined the intracycle V patterns of a group of 16 male national level athletes (8 swimmers and 8 triathlonists), during the first and the last 20 m of a maximum 100 m swim. Rather than reporting instantaneous velocities, the investigators divided the SCs into two phases ('pull' and 'push') and compared the average velocities of each phase. The results showed lower velocities during the pull than the push phases for both arms (with the exception of the first 20 m for the left arm). The patterns of V during the pull and push phases for swimmers and triathlonists are presented in figure 2.2.

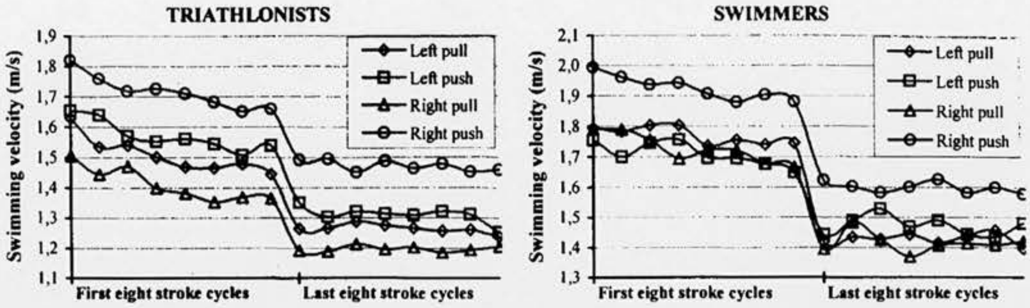

Figure 2.2: Average swimming V in different phases of the SCs during parts of a 100 m maximum freestyle swim
(Adapted from: Keskinen and Keskinen, 1997)

Intracycle V patterns in backstroke swimming have been described only in the study by Maglischo *et al.* (1989). The analysis showed that swimmers reached maximum V at the point that the arm was flexed approximately 90 degrees and/or when the arm was completely extended and below their thigh. The investigators reported distinct periods of V changes in each SC, with two distinct V maxima and minima observed in many swimmers. However, there were differences in the between swimmer V patterns, such as that some swimmers had four V maxima of similar magnitude. Considering that this is the only study conducted in backstroke, it is evident that further research is needed to improve the understanding regarding intracycle V variations in backstroke swimming. Figures 2.3 and 2.4 show the two V patterns presented for the swimmers participating in this study.

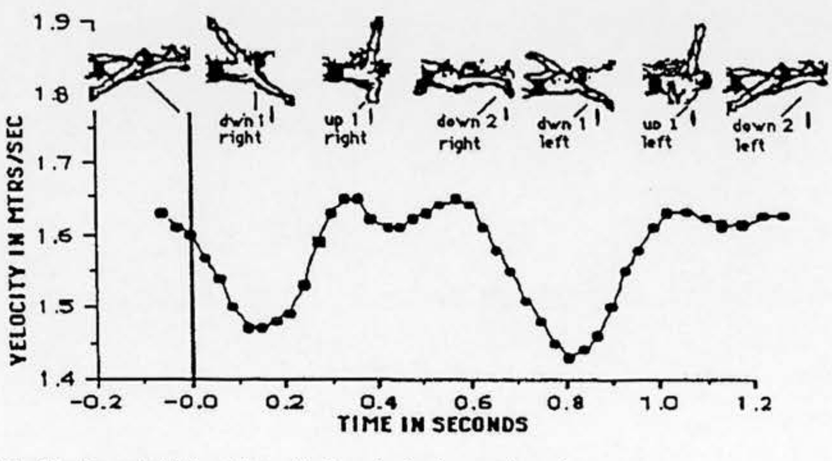

Figure 2.3: Horizontal V pattern in backstroke swimming
(Adapted from: Maglischo *et al.*, 1989)

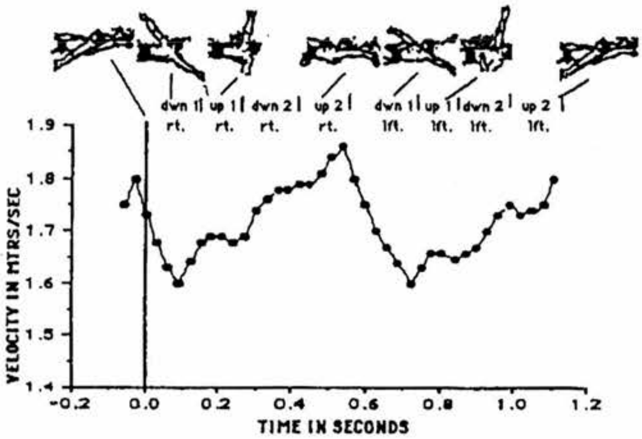

Figure 2.4: Horizontal V pattern in backstroke swimming, using the second upsweep for propulsion
(Adapted from: Maglischo *et al.*, 1989)

Intracycle V patterns in butterfly have been described in only a few studies (e.g. Maglischo *et al.*, 1989; Sanders, 1996b; Barbosa *et al.*, 2003). Maglischo *et al.* (1989) reported that butterfly swimmers showed great variability in the range of V fluctuation. It was also shown that the number of V maxima and minima in a SC varied largely among swimmers. Even though these patterns could have been partially explained by changes in the breathing patters, the latter were not taken into account for the data analysis. Sanders' (1996b) findings were generally in agreement with those of Maglischo *et al.* (1989). Sanders tested seven international level swimmers (four male and three female) and reported that the V maxima and minima differed among swimmers. Figures 2.5 and 2.6 illustrate V profiles for two butterfly swimmers tested in each one of the above studies.

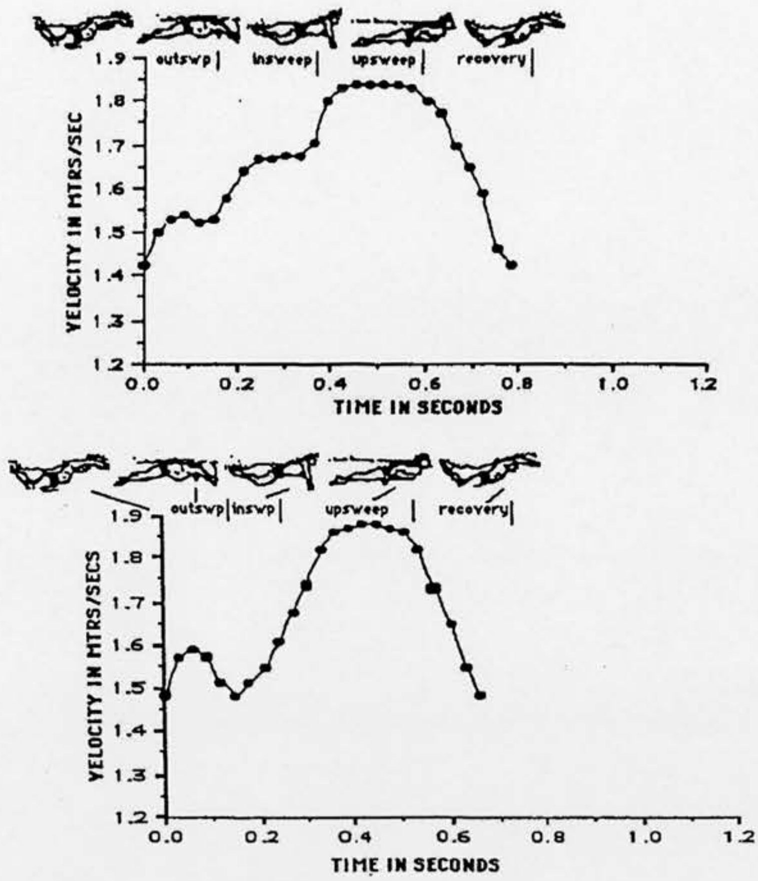

Figure 2.5: Horizontal V patterns for two butterfly swimmers
(Adapted from: Maglischo *et al.*, 1989)

Barbosa *et al.* (2003) attempted to advance the knowledge in intracycle V patterns by investigating whether the intracycle profiles for the hip and CM V were associated for a group of male butterfly swimmers (national and international level, N = 7). These investigators reported that the hip and CM V variations were significantly different, with the magnitude of difference varying according to the breathing actions of the swimmers (lateral/frontal breathing, non-breathing). Both patterns presented large intracycle V fluctuations during the SC. Figure 2.7 shows the intracycle V variations of the hip and the CM of one of the swimmers tested in this study.

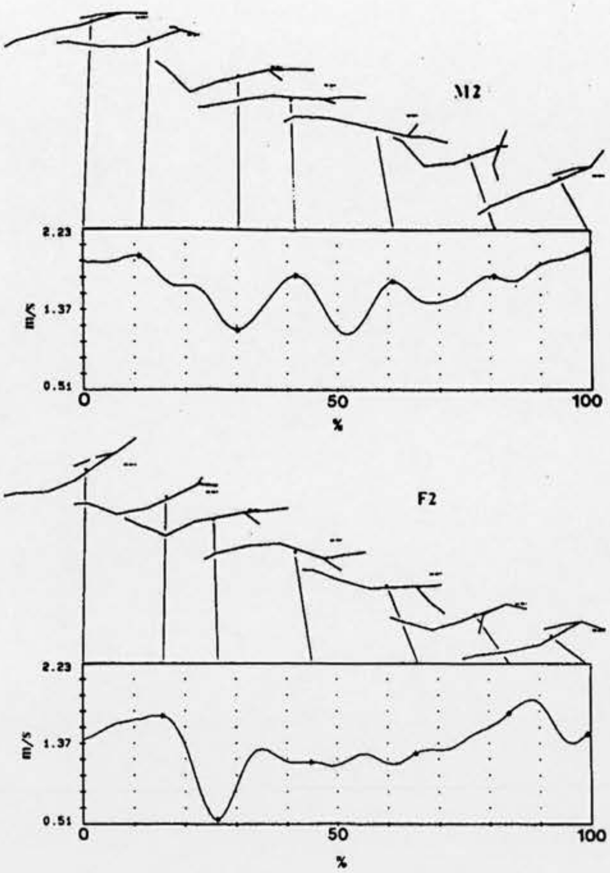

Figure 2.6: Intracycle V profiles for two butterfly swimmers
(Adapted from: Sanders, 1996b)

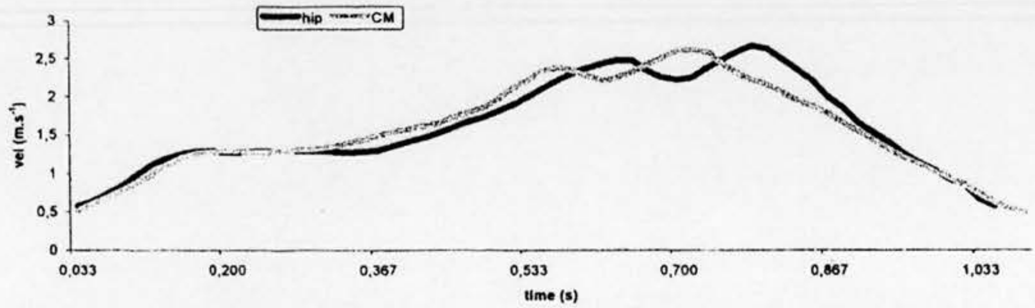

Figure 2.7: Intracycle V profiles of the hip and the CM for a male butterfly swimmer
(Adapted from: Barbosa *et al.*, 2003)

Due to the high variability among swimmers in the personal styles used for breaststroke, the intracycle V variation in breaststroke swimming has attracted the interest of many researchers (e.g. Maglischo *et al.*, 1989; Manley & Atha, 1992; Sanders, 1996a; Colman *et al.*, 1998; Takagi *et al.*, 2004). Researchers agreed that there were many periods of accelerations and decelerations in a SC. Swimmers generally had two distinct V maxima (corresponding to the arm pull and leg kick) and one distinct minimum V (corresponding to the arm and leg recovery phase). Maglischo *et al.* (1989) stated that forward V decelerated markedly during the arm and leg recovery phases. Although this deceleration was unavoidable, world-class breaststrokers seemed to spend less time and have a smaller V fluctuation during the recovery phase than lower level breaststrokers. Moreover, faster swimmers seemed to reach higher minimum intracycle velocities than slower swimmers. Maglischo *et al.* also reported greater intracycle variability in breaststroke, in comparison to the other three strokes. Figure 2.8 shows a typical intracycle V pattern for one of the participants of the latter study.

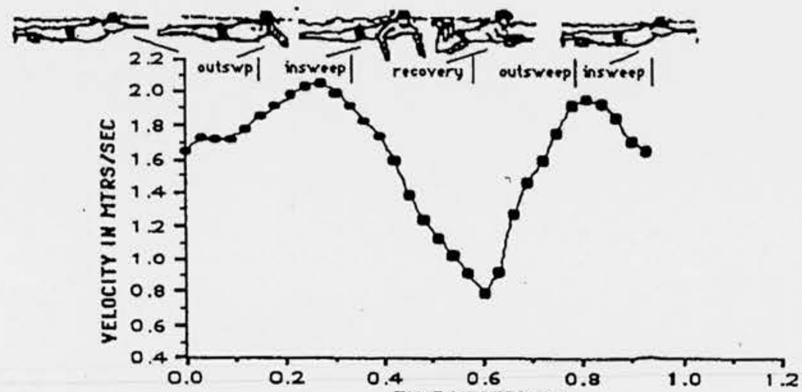

Figure 2.8: Horizontal V pattern in breaststroke swimming
(Adapted from: Maglischo *et al.*, 1989)

2.2.2 Velocity fluctuations

Only a few investigators have calculated the magnitude of V maxima/minima and V fluctuations in butterfly and breaststroke, while the magnitudes of these parameters in freestyle and backstroke remain unknown. Quantitative analysis of the intracycle V in butterfly swimming was first attempted by Togashi and Nomura (1992). These researchers recorded the performance of 25 novice swimmers and indicated that faster swimmers had significantly lower V fluctuations than slower swimmers. The fluctuation in horizontal velocities for all swimmers ranged from 0.19 to 0.43 $m \cdot sec^{-1}$, for average velocities that ranged from 0.95 to 1.60 $m \cdot sec^{-1}$. However, the highest average velocities reported by Togashi and Nomura were similar to those reported for the fastest elite swimmers at a later study (Sanders, 1996b). This should be regarded somewhat surprising, as elite swimmers are expected to have much higher average velocities than novice swimmers. Thus, unexpected differences between the values reported in the two studies could be attributed to differences in the methods used for the calculation of V (as discussed in section 2.2.3).

Manley and Atha (1992) attempted to advance the existing knowledge by calculating intracycle V fluctuations under different pacing conditions. Four male and four female competitive swimmers were tested while swimming at: 50 % of race pace, 100 % of race pace and, increasing from 50 % to 100 % of race pace. Figure 2.9 shows a typical SC pattern for a swimmer during the three testing conditions. Manley and Atha reported that faster swimmers had higher V maxima than slower swimmers. Moreover, swimmers increased V maxima when average V increased. The instantaneous velocities ranged from 0.08 to 0.20 $m \cdot sec^{-1}$ for minimum and from 1.16 to 2.97 $m \cdot sec^{-1}$ for maximum velocities. The average velocities ranged from 0.86 to 1.38 $m \cdot sec^{-1}$. However, the values reported in this study for maximum velocities were much higher than those reported by Sanders (1996a) for swimmers of a higher level. Moreover, the V minima/maxima seemed to be extremely low (close to zero) and high (almost 3 $m \cdot sec^{-1}$) respectively, something that seems rather unlikely given the stroke and level of the participants. A possible explanation could be the method for V calculation. Manley and Atha developed and used a swimming tachometer device. Although the investigators reported several calibration procedures performed for this device, suggesting that the V calculations were accurate, it is possible that the values calculated for V did not represent accurately the true motion of the CM.

Sanders (1996b) conducted the first analysis on elite butterfly swimmers (N = 7) and reported large intracycle fluctuations that varied among swimmers. The range of V fluctuations varied from 0.92 to 1.40 $m \cdot sec^{-1}$, for average velocities ranging from 1.32 to 1.63 $m \cdot sec^{-1}$. Instantaneous velocities ranged from 0.52 to

2.33 m·sec^{-1}. When calculated as percentages of the average SC horizontal V, the fluctuation values represented 56.8 % to 106.1 % of the swimmers' average SC V. Sanders reported that the two slowest swimmers had the largest intracycle fluctuations and the smallest minimum instantaneous velocities, while the second fastest swimmer had the lowest V fluctuation.

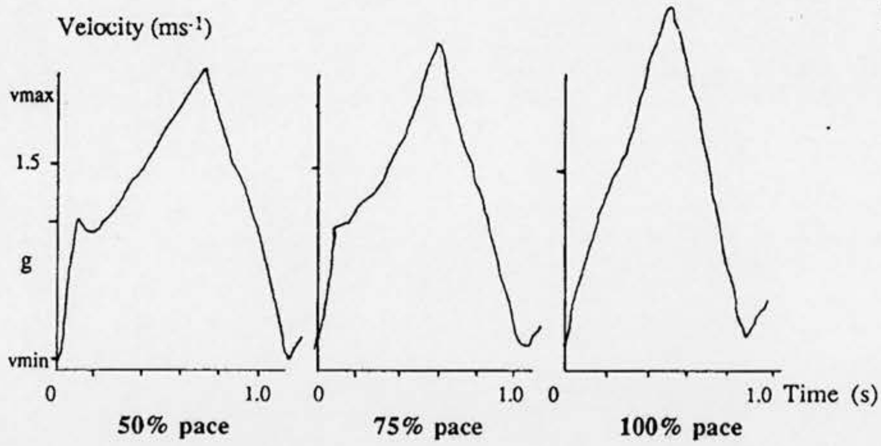

Figure 2.9: Intracycle V profiles for three different pace conditions
(Adapted from: Manley and Atha, 1992)

Sanders (1996a) attempted to improve the understanding of breaststroke kinematics by analysing the intracycle V fluctuations of international level swimmers (three male and three female). High V fluctuations were found, regardless of the gender or the wave action technique (flat or undulating style) of the swimmers. Intracycle V fluctuations ranged from 0.76 (60.3 % of average V) to 1.12 m·sec^{-1} (95.7 % of average V), for average velocities varying from 1.01 to 1.26 m·sec^{-1}. The values for instantaneous V of the CM ranged between 0.45 to 0.86 m·sec^{-1} for minimum and 1.57 to 1.77 m·sec^{-1} for maximum velocities, respectively. The fastest swimmer had the smallest intracycle V fluctuation and the highest minimum V.

Colman *et al.* (1998) attempted to advance further the existing knowledge on intracycle breaststroke V variations, by analysing data for two groups of competitive swimmers with flat and undulating styles (N = 20). Colman *et al.* calculated 2D average V (rather than instantaneous CM V) of stroke phases and reported the mean percentage group fluctuations. The results indicated great intracycle V fluctuation that varied among groups and swimmers, as illustrated in figure 2.10. In agreement with Sander's study (1996a), Colman *et al.* showed that the fluctuations between the V maxima and minima of the body's CM in the most undulating styles (53 % of the average V) were less than in the flattest style (76 % of the average V). However, Vilas-Boas (1996) reported different findings after testing nine national level swimmers in sub-maximal breaststroke velocities (slower than the 200 m race pace). Vilas-Boas showed that the undulating style with above water recovery of the arms might produce higher intracycle V fluctuations than the flat style. Nevertheless, the differences between normal undulating style (with underwater arm recovery) and the flat style were not significant. The latter investigator attributed the discrepancies between the findings of the above studies to possible differences in kinematic and kinetic characteristics between slower and faster breaststroke velocities.

D'Acquisto and Costill (1998) tested 17 trained breaststroke swimmers and investigated the relationships between intracycle V maxima/minima and average V. These investigators stated that better breaststroke sprinters were characterised by their ability to reach higher V maxima and minima during the SC. D'Acquisto and Costill stated that these findings suggested a better streamlined body position and/or timing between the propulsive phases of the stroke for faster swimmers. The relationships between average V and V maxima/minima were also explored in a recent study by Takagi *et al.* (2004). These investigators analysed the performance of 81 male and female swimmers participating in the 50 m, 100 m and 200 m breaststroke events during the 2001 World Swimming Championships. Faster swimmers had significantly higher V minima than slower swimmers. The V maxima did not differ significantly, but the authors reported that faster swimmers showed a tendency to reach higher V maxima. However, there were no significant differences between events or sexes. Although the overall V fluctuations were not correlated with average V, Takagi *et al.* stated that slower swimmers tended to have larger intracycle V fluctuations than faster swimmers.

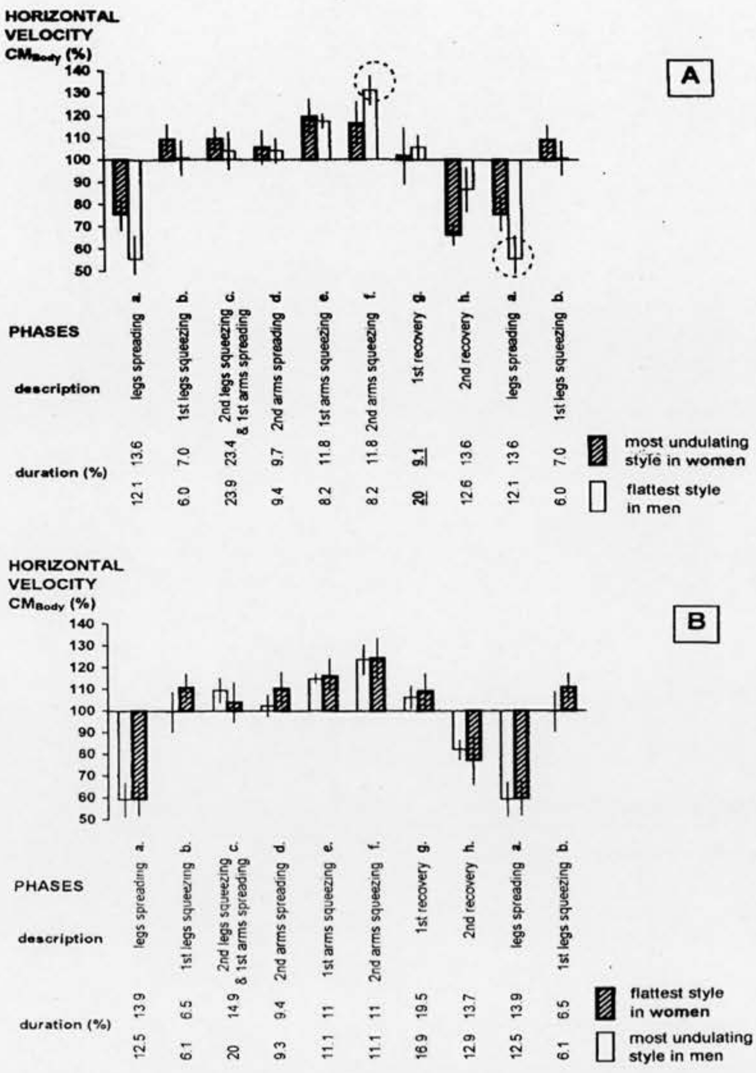

Figure 2.10: Percent horizontal V per phase of the body's CM and the percent duration of the phases, for 5 swimmers with the most undulating and flattest styles, women and men separately
(Adapted from: Colman *et al.*, 1998)

2.2.3 Limitations of the existing studies

Several limitations were identified with regard to the data collection and analysis methods for the studies in this area. This section presents the main limitations of these studies, as well as the areas that remain to be investigated. As explained throughout the section, the existing limitations reduce the usefulness of the reported data and, together with the identified gaps, emphasize the need for further, more sophisticated analysis approaches.

2.2.3.1 Methods for velocity calculation

The most important limitations in this area are associated with the methods employed for the calculation of intracycle V. First, some studies calculated average rather than instantaneous V values for certain phases of the SC (Keskinen & Keskinen, 1997; Colman *et al.*, 1998), limiting the usefulness of the reported data. Second, the horizontal component of the intracycle V of swimmers has been measured as either the V of a fixed point (usually the hip) or the CM. However, several limitations exist when a fixed point is used for V calculations, as discussed in section 2.2.3.1.1 below. In addition to these limitations, most of the studies that examined the V of the CM collected 2D data and calculated the CM based on the assumption of bilateral symmetry. The main limitations of the use of the bilateral symmetry assumption are presented in section 2.2.3.1.2. Furthermore, even though 2D methods might be easier and faster to use in most aquatics laboratories, they do have limited analysis possibilities compared to 3D methods. The advantages of 3D against 2D techniques are described in section 2.2.3.1.3.

2.2.3.1.1 Use of a fixed point

A fixed point on the swimmer's body was used for V calculation in the majority of the studies conducted in this area (Maglischo *et al.*, 1989; Togashi & Nomura, 1992; Vilas-Boas, 1996; Keskinen & Keskinen, 1997; Colman *et al.*, 1998; D'Acquisto & Costill, 1998; Takagi *et al.*, 2004). However, several limitations exist when a fixed point such as the hip is used as indication of CM kinematic parameters, such as V and displacement. For instance, the motion of the hip joint is also dependent on an individual's differing trunk rotations and inertial effects, created by forward or backward leg or arm movements even when no propulsion or resistance is generated (Colman *et al.*, 1998). Furthermore, the 2D calculation of hip kinematics in freestyle and backstroke ignores the rotations of the hips and does not allow calculation of V in directions other than the horizontal.

Barbosa *et al.* (2003) conducted a study to examine whether the V, displacement and acceleration of the hip can represent with validity the kinematics of the CM in butterfly swimming, for three different breathing conditions (frontal, lateral and no inspiration cycles). The hip V had higher intracycle variation than the

V of the CM (e.g. Figure 2.7, section 2.2.1), with the magnitude of difference varying between swimmers and breathing techniques. Barbosa *et al.* emphasised that, even though some correlations were significant, the r values were quite low and, in some cases, negative. The latter finding suggested that for some parts of the SC the trajectories of the hip and CM were not only different but were also moving in different directions. Moreover, the high individual differences between conditions, as well as between swimmers, underlined the reduced validity and reliability of using a fixed point for V calculations. It was concluded that the hip did not represent with validity the intracycle behaviour of the kinematic variables of the CM.

Based on the limitations discussed in this chapter and the findings of Barbosa *et al.* (2003), it could be concluded that a fixed point on a swimmer's body should not be used as an indication of the kinematic parameters of the CM. If this is not possible due to time, equipment or other constraints, researchers wishing to associate any calculated values with those for the CM should report the magnitude of errors for each swimmer, stroke and breathing condition.

2.2.3.1.2 Bilateral symmetry assumption

Some investigators calculated the V of the CM by collecting 2D data and assuming bilateral symmetry (Sanders, 1996a; 1996b). However, the assumption of bilateral symmetry in swimmers' bodies might increase considerably the errors in measurements. Firstly, even if a swimmer's body is perfectly symmetrical, it is still possible for the swimmer to have asymmetries in technique. For example, differences in strength and flexibility between the left and the right body parts may occur during or after periods of injuries. If one extremity is stronger and/or more flexible than the other, then it might follow a different path (or a similar path with different timings for given phases) during the SC. Other factors such as the breathing patterns or individual technique idiosyncrasies might also affect the symmetry in swimming patterns.

- **Asymmetry in anthropometric characteristics and relationships with performance and with technique asymmetry**

Tomkinson *et al.* (2003) stated that many anthropometric traits in humans show a consistent side bias (i.e. directional asymmetry). Based on previous research, these investigators stated that directional asymmetries consistently show a right side bias in the upper limbs. The results of their study supported this argument, as (in a group of 52 athletes) three upper limb girths showed significant right side bias with the left handed athletes representing just the 12% of the group. These results were in agreement with other studies that measured the same anthropometric traits (Laubach & McConville, 1967; Tomkinson & Olds, 2000).

However, asymmetries in anthropometric characteristics are not always associated directly with asymmetric technique patterns and/or performance. McBride (1993) tested 10 asymptomatic runners (diagnosed with a leg length differential) and reported that, regardless of structural status, some runners demonstrated functional equality while others were characterized by functional asymmetry. McBride stated that the prediction of symmetrical/asymmetrical technique pattern was not possible despite the known structural status of the participants. This emphasized the need for the use of 3D methods for accurate analysis of athletes' motion patterns. Tomkinson and Olds (2000) attempted to determine the relationship between symmetry and health-related physiological characteristics in a group of 46 males and females. The data showed no pattern of consistent significant correlations between fluctuating asymmetry and the physiological variables across all traits, failing to confirm the hypothesis that symmetric individuals were physiologically fitter when compared to their asymmetric counterparts. Tomkinson *et al.* (2003) reported no significant differences in variance in fluctuating asymmetry between the 52 male athletes from two sports (basketball and football), competing at two different standards (professional league and semi-professional state league). The investigators stated that asymmetry does not appear to be linked to performance and/or to body size.

- **Technique asymmetries in swimming**

Technique asymmetries and/or lateral dominance have been frequently reported in swimming studies. Arellano *et al.* (2003) identified the asymmetric stroke synchronisation as the second most frequent mistake (observed in about 60 % of the participants) in a group of 177 national level junior swimmers who were studied longitudinally for a period of four years. The qualitative technique analyses of these researchers also showed asymmetric body roll in about 38 % of the swimmers tested.

Higher V values during the right than the left arm stroke have been reported for freestyle and backstroke (Maglischo *et al.*, 1989; Keskinen & Keskinen, 1997). Keskinen and Keskinen (1997) reported that freestyle swimmers and triathlonists had different magnitudes of V fluctuations for certain phases of the left and the right arm strokes. These investigators stated that lateral dominance in arm strength, even though not measured in their study, might have been the principal factor causing the bilateral asymmetries. They also stated that high swimming V during the right arm UWP was most likely connected to the breathing movements, which were to the right in most cases. They also assumed that a non-optimum realignment of the swimmers' bodies after the breathing actions could have resulted in loss of some propulsive force. Payton *et al.* (1999b) indicated that the breathing actions might influence the stroke kinematics in freestyle. In backstroke, as there are usually no major technique modifications while breathing, it is likely that the asymmetries are related to higher strength of the right arm. However differences between right and left side could be caused by several factors, such as: kinematic parameters related to the motion of the upper and lower extremities, body roll and differences in flexibility and co-ordination between body segments.

- **Conclusion on the bilateral symmetry assumption**

The results of the studies discussed in this section indicated that anthropometric asymmetries do not seem to be associated with performance and/or technique asymmetries. However, it was also shown that, regardless of the magnitude of directional asymmetry, technique asymmetries appear frequently in sports movements and vary among individuals. Therefore, it can be concluded that the bilateral symmetry assumption would lead to errors of different magnitudes between participants and could cause important limitations in the analysis and interpretation of the results of a study. Hence, a 3D analysis would be more appropriate for the purpose of minimising such errors, assessing accurately the stroke kinematics and increasing the reliability of a research study.

2.2.3.1.3 Advantages of 3- against 2-D analysis

Although 2D analysis is simpler and cheaper (as fewer cameras and other equipment are needed, less digitising time is required and fewer methodological problems are present), it requires movements to be in a pre-selected movement plane and ignores movements out of the chosen plane (Bartlett, 1997). Yeadon and Challis (1993) stated that this limitation can be important even for events which might appear essentially two-dimensional, such as the long jump. As discussed above, the use of 3D analysis minimises the errors that occur in the calculation of variables such as the V of the CM and, therefore, increases the accuracy and reliability of a study. 3D recording and analysis methods also enable perspective errors to be minimised for any film measurement (Dainty & Norman, 1987). According to Bartlett (1997), further advantages of the 3D analysis are:

- It can show the body's true spatial motions and is closer to the reality of the movements studied.
- It allows inter-segment angles to be calculated accurately, without viewing distortions. It also allows the calculation of other angles which cannot be easily obtained from a single camera view in many cases.
- It enables the reconstruction of simulated views of the performance other than those seen by the cameras (Figure 2.11), an extremely useful aid to movement analysis and evaluation.

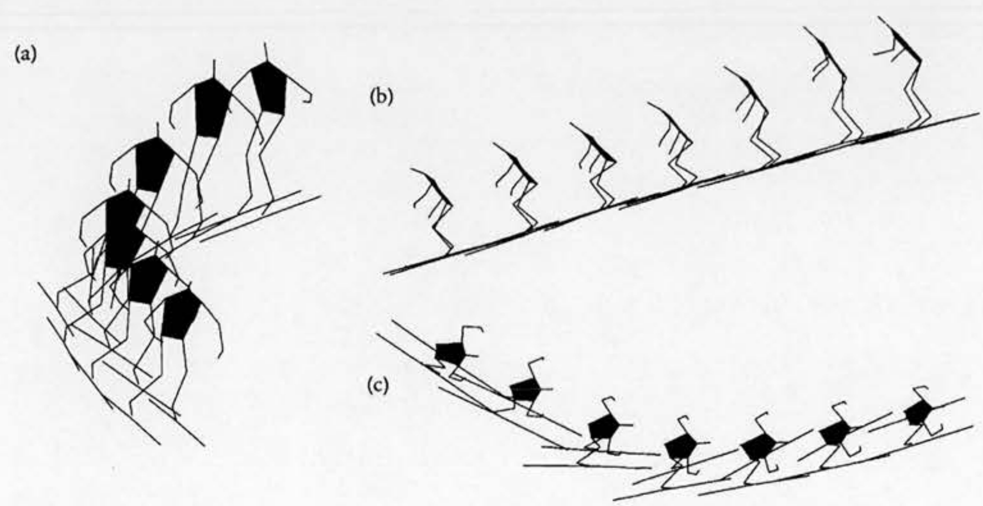

Figure 2.11: Stick figure sequences of a skier: a) front, b) side, c) top view (Adapted from: Bartlett, 1997)

As 2D appears to have several limitations compared to 3D analysis, researchers should favour the latter whenever possible in conducting a biomechanical study. In particular when the objective is the accurate and detailed investigation of movements that occur in more than one plane (such as swimming), the use of 3D analysis techniques is of vital importance for the accuracy, reliability and validity of a study.

2.2.3.2 Other sources of experimental error

In addition to the limitations in the V calculation methods discussed above, experimental errors in the existing studies could have been caused by several other factors. A main source of error was associated with differences in breathing conditions. No studies in this area have considered the influence of breathing actions on the parameters measured and/or the evaluation of the results. However, Barbosa *et al.* (2003) reported that different breathing patterns resulted in large within swimmer differences in V. Other investigators (Payton *et al.*, 1999b; Castro *et al.*, 2003) have also reported differences between breathing and non-breathing conditions for parameters such as body roll and SL. Experimental evidence in the above studies confirmed that the breathing actions (frontal/lateral/non breathing) of swimmers might influence the intracycle kinematics. Therefore, the asymmetries reported in some studies and/or some characteristics in the V patterns could be related to, or partially explained by, the influence of the breathing actions. The latter has to be taken into consideration when discussing or attempting to interpret the results of studies in this area.

Another possible source of errors in studies is the accuracy and reliability of the equipment and analysis methods used. Investigators in this area have only rarely assessed/reported errors associated with the accuracy and reliability of the methodological procedures. Sources of possible accuracy and reliability errors in the existing studies include among others: manual panning of cameras and differences occurring in the 2D viewing angles relative to the swimmers (e.g. Keskinen & Keskinen, 1997); the use of stopwatches for measurement of a test's criterion velocities (e.g. Maglischo *et al.*, 1989); the use of self-constructed devices for V calculations (e.g. Manley & Atha, 1992) and the calibration procedures followed (not reported in most studies).

2.2.4 Areas still to be investigated

One of the main areas that remain to be investigated is the V changes occurring between different SCs throughout the course of a race. Since parameters such as SR, SL and average V are expected to change during a race (e.g. Chatard *et al.*, 2001a; 2001b; 2001c; 2001d), there might be changes in other kinematic parameters related to swimming performance, such as intracycle V fluctuations and V maxima/minima. However, the vast majority of the studies in this area have limited their analysis to one SC. Therefore, it would be of interest to examine any changes that might occur in intracycle V maxima/minima and V fluctuations throughout the course of an event and to assess the whether the magnitude of any changes is linked to swimming performance.

Another major gap in the existing studies was that only the horizontal V component has been examined. Therefore, there is no information about the V fluctuations of the CM in the other two directions. It would be useful to calculate V fluctuations for the vertical and lateral directions and to examine if these fluctuations are associated with performance (as indicated by average V) and/or with fluctuations in the horizontal direction. It would also be of great interest to examine whether the V fluctuations in the vertical/lateral directions change during the course of a race.

Finally, accurate 3D analysis would allow the examination of possible bilateral asymmetries in V patterns (especially in freestyle/backstroke) and identification of the extent to which the magnitude of any asymmetries is associated with the performance level of the swimmers.

2.2.5 Methods for the calculation of the centre of mass

One of the main purposes of this thesis was the accurate calculation of kinematic parameters of the CM. For a precise analysis of human movement, especially for 3D calculations, accurate anthropometric data are required. Such anthropometric data include the mass, volume and CM location of individual body segments and the whole body. As the above cannot be measured directly for living subjects, a method that estimates these parameters must be employed. In order to accurately determine body segment parameters, researchers have used data from studies of cadavers, regression equations, in situ measuring methods, mathematical models or combinations of those. The following sections (2.2.5.1 to 2.2.5.4) present the advantages and disadvantages of the most important methods developed in this area.

2.2.5.1 Cadaver data

Only a few investigators have reported cadaver anthropometric data (e.g. Dempster, 1955; Liu *et al.*, 1971; Becker, 1972; Chandler *et al.*, 1975), with Dempster's data (1955) being the most widely used among researchers. However, a major limitation in all the cadaver studies is that they were conducted on limited numbers of elderly adult males. Therefore, the application of such data to different samples (such as athletes) can be a potential source of errors. Considering the latter, both Dempster (1955) and Chandler *et al.* (1975) pointed out that the data could not be construed to reflect population parameters and should be used with caution.

2.2.5.2 Regression equations

Several researchers have developed regression equations to estimate inertial parameters of the human body. Earlier studies were based on simple measures such as stature and body weight, ignoring differences in other anthropometric parameters such as body shape and mass distribution (e.g. Barter, 1957). Clauser *et al.* (1969) developed multiple regression equations by taking into account subject proportionality differences. Zatsiorsky and Seluyanov (1983; 1985) developed more than 150 regression equations to determine the inertial characteristics and body segments parameters data (weight, location of the CM and radii of gyration) with the use of a gamma-scanner method.

Although these procedures seem to provide accurate anthropometric data on living subjects, several limitations exist. For example, the last two methods (Clauser *et al.*, 1969; Zatsiorsky & Seluyanov, 1983; 1985) require a large number of anthropometric measures for each participant (e.g. 67 measures plus 89 calculations of different indices for the gamma-scanner method), which are time consuming and might cause great inconvenience to the participants. Moreover, the gamma-mass scanning technique involves the use of radiation and, therefore, it has to be established that the procedure is safe for both the participants and the researchers. Furthermore, the use of the latter technique requires sophisticated equipment, which is not available in the vast majority of biomechanics laboratories.

2.2.5.3 In situ measuring techniques

Many research groups have developed measuring devices and methods to estimate in situ the moments of inertia of individual segments (e.g. Bouisset & Pertuzon, 1968; Hatze, 1975; Allum & Young, 1976; Stijnen *et al.*, 1983). The main limitation of these studies was the inaccessibility of many of the body segments and axes, as well as the establishment of accuracy and reliability of the developed methods/devices. Other investigators have used computed tomography to estimate the segment density and mass distribution (e.g. Huang & Suarez, 1983; Mungiole & Martin, 1986; Ackland *et al.*, 1988). This method estimates small increments of volume and tissue density from 3D computer images. A major limitation of computed tomography is that it has not been used yet to provide complete estimates of inertial characteristics. Moreover, the complexity of the method and the need for sophisticated equipment makes its application difficult, time consuming and impractical.

2.2.5.4 Mathematical models

2.2.5.4.1 Early models

Mathematical models of the human body are based on the representation of the segments by standard geometric shapes. The models can vary in the number of segments they contain and can be 2D or 3D. A simple approach that was used in earlier studies (Whitsett, 1963; Hanavan, 1964) assumed that each segment is a single homogenous solid such as a right elliptical cylinder or a frustum of a right circular cone. Anthropometric measures on the subjects provided the dimensions of the shapes, while the segment mass was estimated with the use of regression equations based on cadaver studies (Barter, 1957). Whitsett (1963) developed a mathematical model for a 14-segment body, while Hanavan (1964) developed a 15-

segment body model. While Whitsett's model was not validated against a known set of data, Hanavan validated his model against the data of Santschi *et al.* (1963) (66 subjects) and reported that the location of the CM was within ± 1.8 cm, approximately, of experimental values. However, Hanavan recognised in his report (1964, p.39) that the single homogenous solid assumption fails to take into consideration the shape fluctuations throughout the length of each segment. Chandler *et al.* (1975) also examined the Hanavan model against the data for six cadavers, after using some modifications made to the model by Tieber and Lindemuth (1965). Chandler *et al.* found errors that ranged from 4.4 to 112.5 % for the moments of inertia, and stated that the ellipsoidal head, the elliptical cylinder trunk and the spherical hands were least acceptable. Even though further modifications improved the accuracy of the predictions of the model, Chandler *et al.* concluded that the shapes used to model the segments were not adequate. In support of the latter, Jensen (1978) stated that such models are of questionable accuracy because of the extensive geometrical and mass distribution assumptions.

2.2.5.4.2 The elliptical zone method

The assumption that the human body is composed by elliptical zones was originally made by Weinbach (1938). Weinbach calculated the volume of some segments and of the whole body and, assuming a fixed body density, estimated the body weight. Dempster (1955) evaluated the accuracy of Weinbach's method and found it to be very good with the exception of the shoulders. Jensen (1976) developed a mathematical model in which the body was divided into 16 segments. Each segment was considered to be composed of elliptical zones two centimetres wide, in order to follow effectively the shape fluctuations of the segment (Figure 2.12). The axes of the elliptical zones were obtained using photographic records of the side and front view of the participants, taken simultaneously while the participants assumed the basic anatomical position. Segment densities were taken from the literature and were assumed to be uniform for each segment. Segment mass, volume, CM location, total body mass and CM location are the main parameters that can be calculated with this method.

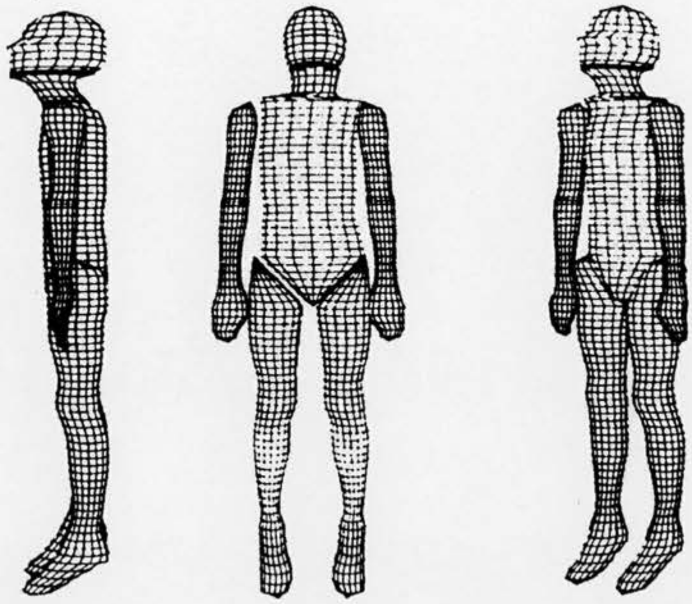

Figure 2.12: Elliptical zone representation of the segments with the body in the reference configuration
(Adapted from: Jensen & Nassas, 1988)

Ackland *et al.* (1988) investigated the validity of the uniform density assumption for the leg segments and indicated that, even though density was not uniform throughout the segments, the adoption of this assumption when modelling the human body produced only minor errors. Wei and Jensen (1995) constructed segment density profiles and compared segment inertias calculated when uniform densities and profile densities were used in a mathematical model. The latter investigators stated that neither method was shown to produce more accurate results than the other.

Jensen (1978) stated that when both the elliptical zone and the Hanavan method were used to estimate body mass of 12 children, the mean errors were -0.68 % and -12.36 % for the elliptical zone and the Hanavan method, respectively. This finding indicated that the former method was more accurate for the tested sample. Jensen also stated that the accuracy of the estimates in total body mass was high (considering the possible sources of error due to both segment volume and the assumed segment density) and that variations in the error of the estimates between subjects were low.

The accuracy of the elliptical zone method was established for different samples in numerous research studies. Yokoi *et al.* (1985) investigated the differences in body segment parameters of 91 children and reported average differences between estimated and measured values of 1.14 % for the body mass and 1.82 % for the location of the body's CM. Finch (1985) reported mean errors in total body mass of 0.77 ± 0.29 % for a sample of college females. Jensen (1986a) investigated the effect of growth on selected segmental size for 12 boys over a 3-year longitudinal study. The mean error in the estimated total mass was 0.20 ± 2.30 % and the method was shown to be better than other techniques. Sanders *et al.* (1991) reported errors of 0.35 ± 3.00 % in body mass estimates, and stated that the discrepancy between the actual whole body mass and the calculated whole body mass was redistributed to the segments on a proportional basis. Jensen and Fletcher (1994) reported a mean error of 0.05 ± 2.96 % for body mass estimation, for a sample of 19 elderly subjects.

A recent study by Wicke and Lopers (2003) attempted to determine the accuracy of the elliptical zone method for identifying segment volumes in male and female university students of various morphologies. No significant differences were found between sexes in the volume estimation, confirming that the elliptical zone method was sensitive to variations in shape. The results showed that the volumes of several segments and the whole body can be accurately measured using the elliptical zone method. The use of a larger image ratio (1:5) decreased significantly the mean volume errors recorded for a 1:10 ratio. The investigators recommended the use of larger image sizes for increased accuracy in segmental volumes.

In view of the results of the studies discussed in this section, the elliptical zone method appears to have a number of advantages compared to other methods and techniques used for the calculation of body segment parameters. First, the elliptical zone method appears to be accurate regardless of the sample tested, and to produce smaller errors than other methods. Second, it effectively follows body shape fluctuations and minimises the inconvenience to the subject, as the marking and filming time is very short. In addition, in many cases the marking of the participants is the same as the marking used for the experimental part of a study, increasing therefore the accuracy and reliability of the research. Finally, the calculation of the anthropometric parameters requires standard filming equipment and biomechanical techniques that are available in most biomechanical laboratories.

2.3 Other kinematic parameters related to velocity

As discussed in the previous sections, it has been indicated that swimming V changes constantly during a SC. Therefore, it would be reasonable to expect that there would be intracycle changes in other kinematic parameters that are associated with V. The following three sections present the kinematic parameters that have been linked to the changes in V and are related to the motion of the trunk (section 2.3.1), the upper (section 2.3.2) and the lower extremity (section 2.3.3). The methodological limitations and the gaps in the studies conducted in this area are also presented in these sections.

2.3.1 Kinematic parameters of the trunk: body roll

The main kinematic parameter of the trunk that has been linked to freestyle swimming performance is body roll. Body roll can be defined as the rolling action of the trunk around its longitudinal axis. Counsilman (1968) suggested that body roll has a number of important functions in swimming, as it could: make the recovery of the arm easier and permit a shorter radius of rotation of the recovery arm; place the strongest part of the arm pull more directly under the CM; place the hips in such position that the feet can be thrust partially side-wards, thus cancelling the side-wards way of the torso possibly created by the forward swing of the recovery arm; facilitate the breathing action etc. Moreover, studies in the area of sports medicine suggested that body roll reduces the risk of developing shoulder injuries (Richardson *et al.*, 1980; Ciullo & Stevens, 1989; McMaster *et al.*, 1989).

In view of the possibility that body roll may play an important role in freestyle swimming performance, researchers attempted to determine the effect of body roll on some kinematic parameters with the use of computer simulation models (Hay *et al.*, 1993; Payton & Mullineaux, 1996; Payton *et al.*, 1997). Other investigators tried to measure and assess the influence of body roll in stroke kinematics and swimming performance during tests (Liu *et al.*, 1993; Payton *et al.*, 1999a; 1999b; Yanai, 2001; Castro *et al.*, 2003; Yanai, 2003) and competitions (Cappaert *et al.*, 1995; 1996; Cappaert, 1999).

2.3.1.1 Computer simulation studies

Hay *et al.* (1993) developed the first simulation model to examine the effect of body roll on hand path during the pull phase in freestyle swimming. The trunk and right arm were modelled as two rigid segments, joined at the shoulder by a simple hinge joint (Figure 2.13). The rigid arm segment was assigned a pre-selected elbow flexion angle and the hand was made to move in a plane through the shoulder parallel to the sagittal plane of the rotating trunk. Based on the results, the investigators suggested that when body roll exceeds the amount necessary to produce the desired medial deviation of the hand, the swimmers must move the arm away from, rather than towards to, the trunk's midline.

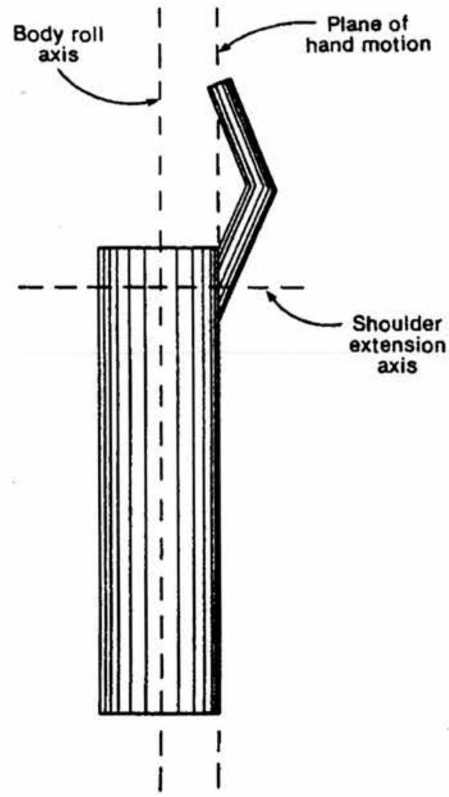

Figure 2.13: Overhead view of the two-segment model
(Adapted from: Hay *et al.*, 1993)

In more recent computer simulation studies (Payton & Mullineaux, 1996; Payton *et al.*, 1997), investigators attempted to improve the rigid arm model developed by Hay *et al.* (1993), by modelling the right arm as two rigid segments hinged at the elbow to enable flexion and extension (Figures 2.14 and 2.15). The arm was also linked to a rigid trunk with a joint capable of shoulder extension and shoulder abduction/adduction. These studies showed that body roll seemed to assist in the development of propulsive forces and, therefore, the improvement of swimming performance. Nevertheless, the investigators underlined that the validity of these studies had yet to be established and the results should only serve as preliminary indications of the influence of body roll in kinematic parameters of swimming.

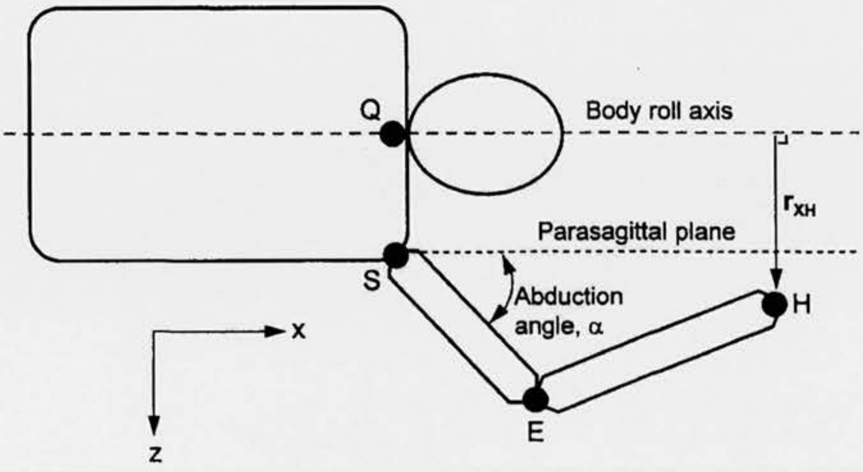

Figure 2.14: Body roll model viewed from above
(Adapted from: Payton *et al.*, 1997)

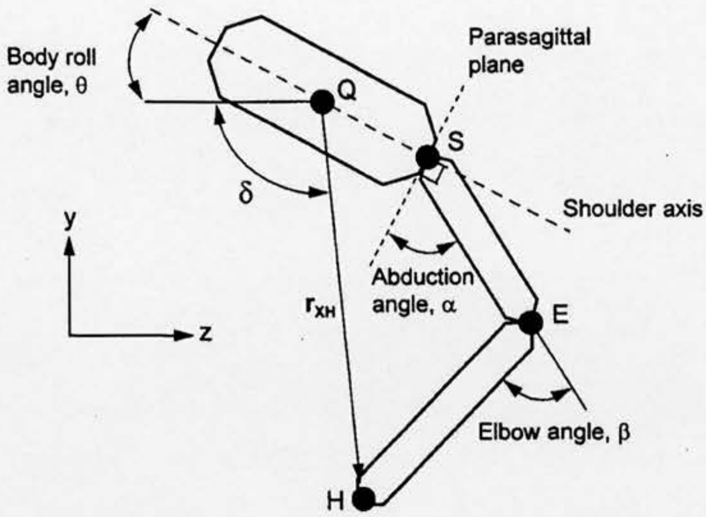

Figure 2.15: Body roll model viewed from behind
(Adapted from: Payton *et al.*, 1997)

2.3.1.2 Experimental studies

Body roll was measured for the whole trunk in the majority of studies in this area (Liu *et al.*, 1993; Payton *et al.*, 1999a; 1999b; Castro *et al.*, 2003). A balsa wood fin mounted on a curved aluminium base was strapped to the back of each subject and body roll was defined as the angle between the rear end of the fin and the vertical (Figure 2.16). Liu *et al.* (1993) conducted one of the first experimental studies to calculate body roll, in an attempt to determine the influence of body roll on the medial-lateral component of the path followed by the hand during the propulsive phase of swimming. The maximum body roll angle for the ten male university swimmers ranged between 51.5° and 66.0° (mean: 60.8 ± 4.4°). It was reported that the contribution of body roll to the actual hand path was nearly equal to the contribution of the medial-lateral motions of the hand relative to the trunk.

Payton *et al.* (1999a) attempted to advance the knowledge with regard to body roll in swimmers of higher level, after testing six male competitive swimmers. It was shown that body roll had a negative contribution to hand speed during the insweep phase and that swimmers would have reached 46 % (± 15 %) higher hand V on average for that phase. Nevertheless, the investigators underlined that this should not be interpreted as meaning that the swimmers would achieve higher hand speeds by rolling less, as any changes in body roll are likely to be accompanied by compensatory changes at the shoulder and the elbow.

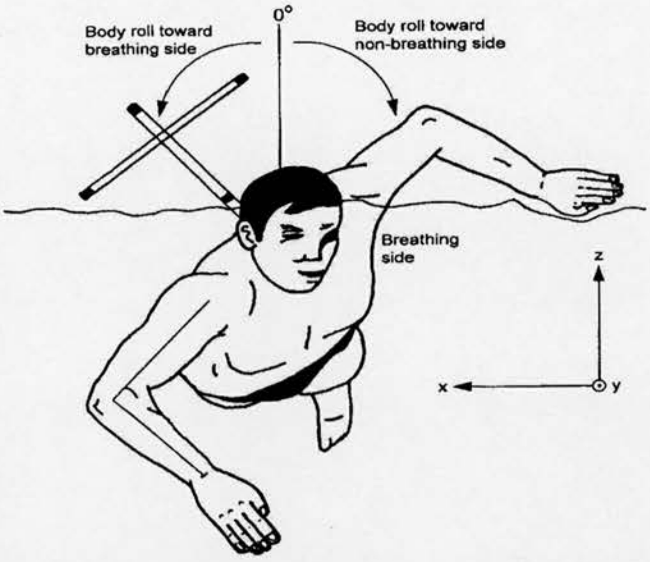

Figure 2.16: Method used for body roll calculation
(Modified from: Payton *et al.*, 1999b)

Payton *et al.* (1999b) investigated body roll differences according to breathing conditions, for six male competitive swimmers tested during preferred side breathing and breath-holding freestyle swimming. The researchers reported that the swimmers' body was rolling on average 9° more when breathing (66 ± 5° for breathing and 57 ± 4° for the non-breathing conditions). It was suggested that the additional body roll would assist the turning of the head and help bring the mouth clear of the water, without the swimmer having to lift or turn the head excessively relative to the shoulders.

Castro *et al.* (2003) conducted further analyses in competitive male swimmers (N = 10), attempting to investigate the relationship between body roll and average swimming V. These investigators examined the performance of swimmers at three different velocities (warming up, 1500 m and 50 m pace) and two different breathing conditions (breathing to the preferred side and no breathing). It was generally indicated that the body roll of swimmers decreased with increasing V and during the non-breathing (compared to the breathing) condition. As expected, swimmers rolled less to the non breathing side.

For the purpose of improving the understanding of body roll kinematics in freestyle, Yanai (2001; 2003) calculated separately the shoulder and hip roll of eleven male university swimmers. Shoulder roll was defined as the angle between the line connecting the shoulder joint centres projected onto transverse plane of the trunk (the plane perpendicular to the long axis of the trunk) and the line intersecting the transverse plane and the horizontal plane. Similarly, the line connecting the hip joint centres was used for the calculation of hip roll. Yanai (2001) reported mean angles of 58° (confidence intervals: 52° to 65°) for shoulder and 36° (confidence intervals: 29° to 43°) for hip roll. However, Yanai (2001) did not calculate the average V of the swimmers and, therefore, the relationship between V and shoulder/hip roll was not assessed. In the more recent study (2003), Yanai reported that swimmers decreased shoulder roll by 9° when swimming V increased from 1.3 to 1.6 $m \cdot sec^{-1}$.

2.3.1.3 Competition analyses

Body roll was calculated separately for hips and shoulders in three studies (Cappaert *et al.*, 1995; 1996; Cappaert, 1999) conducted during major swimming competitions (1992 and 1996 Olympic Games; 1991 World Championship). In all three studies the shoulder joints were digitised for both the above and below water views and adjustments were made where appropriate to combine the data. It was reported that elite 100 m freestyle swimmers [participating in the finals of the events (N = 5)] rolled their shoulders and hips towards the same direction, but the shoulders rolled considerably more than the hips (Cappaert *et al.*, 1995; 1996). Nevertheless, two elite swimmers (including the gold medallist) had equal amounts for shoulder and hip roll. Subelite swimmers [participating in the preliminary heats of the events, (N = 7)] appeared to have similar values to elite swimmers for shoulder and hip roll, but the hips were rolling to the opposite direction of the shoulders. The mean values reported for shoulder and hip roll were 34.4 ± 1.7° and -17.8 ± 1.5° for the subelite group and 35.4 ± 2.5° and 8.3 ± 1.5° for the elite group. Cappaert (1999) also reported that sprint freestyle swimmers (200 m and below, N = 5) have less shoulder roll during the catch phase than distance freestyle swimmers (above 200 m, N = 4) (20.9° and 36.9°, respectively).

Body roll patterns were reported for some 100 m and 200 m backstroke swimmers (Cappaert *et al.*, 1996; Cappaert, 1999). Similar to freestyle, elite swimmers were rolling the shoulders and hips in phase, whereas the subelite swimmers were not. According to the researchers, opposite body roll has two potential disadvantages: 1) it adversely affects the streamlining of the body and, 2) this body position tends to decrease the use of the trunk muscles during the pulling pattern. However no values were reported for the shoulder and hip roll in either of the above studies.

Cappaert *et al.* (1995) stated that the competition analyses implied that faster swimmers use body roll more efficiently than slower swimmers, reducing the active drag and therefore improving performance. Moreover, it was suggested that the opposite roll between the shoulders and hips of the subelite group might have increased active drag, as the downward motion of the hip increased frontal surface area. The competition data emphasised that for accurate identification of the rolling parameters of the trunk, roll has to be calculated separately for shoulders and hips.

2.3.1.4 Limitations of the existing studies

2.3.1.4.1 Computer simulation studies

Several limitations existed in the methodology of the computer simulation studies. First, Hay *et al.* (1993) assigned a fixed value for the elbow angle, something that was shown to be incorrect by later studies (e.g. Cappaert, 1999; Duclos *et al.*, 2003). Moreover, Liu *et al.* (1993) demonstrated that it was unrealistic to constrain the hand to move in the parasagittal plane described in the above study, because the swimmers move their hands laterally relative to this plane. Second, all simulation models were based on the assumption that the trunk moves as a rigid part during freestyle swimming. However, other investigators (e.g. Cappaert *et al.*, 1995; Yanai, 2001) proved that the assumption that the whole trunk rolls as a rigid segment is not tenable because the shoulders and hips roll to different extents and in some cases with different phase. Finally, the computer simulation models assumed that the trunk rolls away from the neutral position and that the arm rotates laterally relative to the rolling trunk for the duration of the insweep. However, these assumptions were also proved to be incorrect by later studies (e.g. Payton *et al.*, 1999b; 2002).

2.3.1.4.2 Experimental and competition studies

While the studies in this area provided some useful data on body roll and suggested that it is associated with swimming performance, important limitations in the methodological procedures reduce the usefulness and applicability of the reported data. A major limitation in most studies conducted during swimming tests (Liu *et al.*, 1993; Payton *et al.*, 1999a; Payton *et al.*, 1999b; Castro *et al.*, 2003), was that body roll was measured for the whole trunk. However, as discussed above (section 2.3.1.4.1), the assumption that the trunk moves as a rigid part ignores differences in the magnitude and phase of shoulder and hip roll (e.g. Cappaert *et al.*, 1995).

Another major limitation in most experimental (Liu *et al.*, 1993; Payton *et al.*, 1999b; Yanai, 2001; 2003) and in all competition studies (Cappaert *et al.*, 1995; 1996; Cappaert, 1999) was that the breathing actions of the swimmers were not taken into account for the subsequent calculations of the parameters and the interpretations of the findings. The latter limitation reduces the accuracy and reliability of the reported data, as it has been shown that the breathing action influences body roll values in freestyle swimming (Payton *et al.*, 1999b; Castro *et al.*, 2003).

Moreover, all studies reported average roll values assuming bilateral symmetry, despite the fact that asymmetries in body roll (Arellano *et al.*, 2003) and other kinematic parameters (Maglischo *et al.*, 1989; Keskinen & Keskinen, 1997) have been reported frequently in swimming studies.

Furthermore, the small number of below water cameras used in most studies reduces accuracy, due to the potentially large number of non-visible body landmarks that would require the operator's guessed estimation for their location. Reliability of kinematic parameters calculation might also be a source of experimental error. Nevertheless, reliability calculations have been reported only in a few studies (SD in hip roll calculation was 2.5° in the following studies: Payton *et al.*, 1999a; 1999b; 2002).

Challis (1995) reported that extrapolations beyond the calibrated space produced errors up to three times (or up to 14.5 mm) larger than errors produced for the space normally calibrated. The length of the calibrated space in all competition analyses in this area was just 2 m. However, during a SC a swimmer would cover a distance that would be equal to the length of their body when the arm is extended plus the length covered during the SC. Therefore, it is certain that extrapolations well beyond the pre-calibrated space were required for considerable parts of the analysed SCs, thus reducing the accuracy and reliability of the studies. Although Cappaert *et al.* (1995) accepted that extrapolations beyond the 2 m horizontal calibrated space in their study could have caused inaccuracies, the magnitudes of these errors were not estimated.

Further sources of errors were identified in some experimental studies (Yanai, 2001; 2003). As stated by Yanai *et al.* (1996), the periscope system used in the former studies could have resulted in image distortion and light refraction errors caused by the structure of the lens of the camcorder and the refraction at the interface of water. Furthermore, the adjacent volumes calibrated for the multiphase calibration procedure did not overlap. In practice, the latter meant that when the panning orientations of the pairs of cameras fall in adjacent volumes, then only one calibrated volume could be used and extrapolations beyond this volume would increase digitising errors (Challis, 1995). Finally, inter-operator differences in the panning speeds and orientations of the two periscope cameras resulted in camera orientations falling into different calibration volumes for a certain field, decreasing therefore the reliability of the calculated parameters due to differences in the reliability of adjacent calibrated volumes.

2.3.1.5 Areas still to be investigated

Similar to the intracycle V studies, body roll has been calculated only for one SC. Therefore, there is a lack of information regarding changes that might occur in shoulder and/or hip roll throughout the course of an event. Moreover, shoulder and hip roll need to be calculated for both sides, as bilateral asymmetries might exist and could influence the interpretation of the results of a study. Furthermore, it would be of interest to examine whether the magnitude of bilateral asymmetries is associated with the performance level of the swimmers.

2.3.2 Kinematic parameters of the upper and lower extremity

2.3.2.1 Kinematic parameters of the upper extremity

Only a few investigators have examined the changes in kinematic parameters of the upper extremity in relation to swimming V. The main parameter that has been found to be associated with swimming V was the angle of MEF during the UWP of the stroke. Cappaert *et al.* (1995) reported statistically significant differences ($p<.05$) between elite and subelite swimmers for MEF angles, suggesting that MEF is associated with swimming V. The minimum elbow angles (representing MEF) reported during the UWP of the stroke were $91.5 \pm 4.9°$ for elite and $114.3 \pm 5.1°$ for subelite swimmers. The importance of the elbow angle in swimming performance was emphasised by Cappaert (1999), who reported that the elbow angle had the highest impact on the freestyle stroke and that a straighter arm was associated with a longer pulling pattern and slower SR.

Similar patterns were reported by Duclos *et al.* (2003), who compared two groups of elite (Olympic Games finalists, N = 4) and subelite (competing at the French national championship, N = 3) swimmers performing a 200 m maximum freestyle swim. Elite swimmers pronounced the flexion of the elbow more than subelite swimmers. The investigators stated that elite swimmers did not change their joint angles significantly during the last length of the race, while subelite swimmers exhibited erratic coordination of their upper limbs. The angular variations reported for some parts of the SC in the first and the last 50 m for the elbow joint were: 28.9° and 38.7° (elite) and, 17.4° and 2.2° (subelite).

Changes in the angular ROM of the elbow have not been adequately studied in backstroke and breaststroke. In butterfly, Togashi and Nomura (1992) reported that faster swimmers tended to have smaller angles for the elbow joint during the catch phase. However, in addition to the limitations of this study (discussed in section 2.2.4), the values reported for the range of elbow angles (128.0° to 240.6°, SD = 2.8°) suggested errors in the calculation or the presentation of the data.

Only a few other upper extremity kinematic parameters, such as the displacements of the elbow and wrist, have been examined in relation to freestyle swimming V. However, these parameters have not been found to be associated with changes in V. For example, Cappaert *et al.* (1995) found that elite swimmers had a deeper pulling pattern than subelite swimmers, which, however, was due to the greater stature of the former group. No differences were found in the vertical displacements of elbow and wrist when the values were normalised according to the anthropometric characteristics.

2.3.2.2 Kinematic parameters of the lower extremity

Very few investigators have examined the changes that occur in kinematic parameters of the lower extremity and their influence in freestyle swimming V. The main parameter that has been found to be associated with swimming V was the MKF angle. Early studies in this area (Gollnick & Karpovich, 1964; Sheeran, 1978; 1980) used the electrogoniometer (a device that measures continuous changes in degrees of joint angles during motion), which was developed by Karpovich and Karpovich (1959). Golnick and Karpovich (1964) reported a range of motion (ROM) of 45° for freestyle kick (130° to 175°), 60° for butterfly kick (120° to 180°) and 120° for breaststroke kick (55° to 175°). However, just one subject was tested for the above study, with no information regarding his/her swimming level and stroke specialisation, the SCs selected for analysis, the test used etc. Thus, the reported data could only be considered as a first indication of possible knee angles in swimming.

Sheeran (1978; 1980) provided the first set of data on MKF for a group of swimmers. Sheeran examined the knee ROM differences between butterfly, backstroke and freestyle kicks analysed for 10 (1978) and 14 (1980) university swimmers. It was generally shown that the knee movement was similar for freestyle and backstroke, but different for butterfly. Sheeran reported significant differences for some pairs of variables between and within studies. Moreover, large differences in MKF were found between the two studies. Possible explanations could be differences in the level of the participants, the SCs selected for analysis, the kicking V and/or the kicking pattern used by swimmers in the two studies, none of which were specified by the investigator.

Cappaert *et al.* (1995) advanced the knowledge with regard to MKF by testing a sample of competitive swimmers. Cappaert *et al.* indicated that elite 100 m freestyle swimmers had a higher ROM (58.2 ± 5.9°) compared to subelite swimmers (49.3 ± 5.2°). Similar patterns have been reported for backstroke, as the mean value for knee ROM of elite backstroke swimmers was 61.0°, compared to 43.6° for subelite swimmers (Cappaert *et al.*, 1996). The results in both studies suggested that higher MKF is associated with faster swimming V. That was in agreement with a later study by Cappaert (1999), who compared sprint (up to and including 200 m events, N = 5) and distance (above 200 m events, N = 4) freestyle swimmers and reported that sprinters were characterised by more MKF. The minimum knee angles were 100.8° and 139.7° for sprint and distance freestyle swimmers, respectively. The investigators claimed that a larger MKF would be beneficial as it will give the foot a larger ROM to produce propulsive forces.

2.3.2.3 Limitations of the existing studies

The studies presented in the last two sections showed that the maximum flexion angle of the elbow (during the UWP of the stroke) and the knee seem to be associated with swimming performance. Nevertheless, limitations in the existing studies reduce the accuracy and reliability of the reported data.

First, as discussed before, the breathing action has been found to alter swimming kinematics. However, similar to the limitations reported for the studies measuring intracycle V and body roll, the breathing actions of the swimmers were not taken into account when collecting and analysing the data for all studies in this area. Second, despite the possibility of bilateral asymmetries (e.g. Maglischo *et al.*, 1989; Arellano *et al.*, 2003), all studies in this area calculated values for only one side, assuming bilateral symmetry. Moreover, despite the angular motion of the elbow and knee joints requiring a multi-planar analysis, some studies restricted their analysis to 2D (e.g. Duclos *et al.*, 2003). Furthermore, the 3D studies (Cappaert *et al.*, 1995; 1996; Cappaert, 1999) were prone to errors due to extrapolations beyond the small volume of the calibrated space, as discussed in section 2.3.1.4.2.

Further sources of experimental error were identified in some studies. For example, Duclos *et al.* (2003) tested only the national level swimmers, while the data for elite swimmers were obtained from television broadcasts of Olympic Games. Despite the investigators claiming the use of a protocol 'simulating the Olympic Games competition', the practise of combining and comparing data obtained in different pools, with different equipment and under different conditions, is potentially problematic. Moreover, the angular patterns were not calculated for the full SC and, therefore, did not reflect the complete elbow angular patterns during the UWP of the stroke.

2.3.2.4 Areas still to be investigated

Likewise intracycle V and body roll, MKF and MEF angles have been calculated just for one SC in all studies conducted in this area. It would be of interest to calculate any changes in these parameters throughout an event and examine whether the MKF and MEF values are associated with swimming V. In addition, analysis of MKF and MEF for the left and right sides could be informative in terms of identifying bilateral asymmetries and their association with swimming V.

2.4 Summary

The following sections summarise the main research findings, limitations and gaps in the scientific areas reviewed in this chapter.

2.4.1 Intracycle velocity

- **Main findings of the existing research**

For the purpose of detecting more specific V changes within a SC and their association with performance, many research teams have studied the intracycle fluctuation of swimming V. The review of the literature showed that:

- Swimming V changes constantly during a SC.
- For butterfly and breaststroke, faster swimmers appear to have lower V fluctuations and higher V maxima/minima than slower swimmers.
- Technique asymmetries have been found for the aquatic phases of the left and right arm in freestyle.

- **Limitations of the existing research**

The most important limitations of studies in this area are as follows:

- Calculation of the V of a fixed point, despite not reflecting accurately the V of the CM.

- Adoption of the bilateral symmetry assumption, despite the asymmetrical technique patterns identified in many studies.
- Other experimental limitations such as: limited number of cameras and/or participants used; insufficient presentation of calibration procedures, error estimation and methods' reliability assessments.

- **Areas to be investigated**

The major gaps in the existing literature are the following:

- Only the horizontal component of V has been examined.
- The relationships between V fluctuation/maxima/minima and swimming performance have not been studied for freestyle and backstroke.
- The changes that might occur in intracycle V fluctuations during the course of the race remain to be investigated.
- Researchers have not attempted to calculate possible bilateral asymmetries and their influence on swimming performance.

2.4.2 Other kinematic parameters related to velocity

The review of the literature showed that several kinematic parameters related to the motion of the trunk, the upper and the lower extremity, are associated with changes in swimming V.

2.4.2.1 Kinematic parameters of the trunk

- **Main findings of the existing research**

Body roll is the main kinematic parameter of the trunk to be linked to swimming V. The effect of body roll on some kinematic parameters has been examined with the use of computer simulation models. In addition, the influence of body roll in swimming performance has been measured during tests and competitions. The major findings of the existing research are the following:

- Body roll influences hand V and displacement, and might assist in the generation of propulsive forces in freestyle.
- The magnitude of body roll is affected by the breathing action.

- Elite swimmers roll their shoulders and hips towards the same direction, contrary to subelite swimmers.
- Shoulders appear to roll considerably more than the hips.
- Analysis of some phases of the SC showed that sprint freestyle swimmers have less shoulder roll than distance freestyle swimmers.
- Swimmers seem to increase shoulder roll when V decreases.
- Faster swimmers appear to use body roll more effectively than slower swimmers, reducing the active drag and therefore improving performance.

- **Limitations of the existing research**

Several limitations in the existing studies reduced the validity and applicability of the reported data:

- The computer simulation models had limited reliability and applicability.
- In many studies, body roll was measured for the whole trunk. However, the assumption that the trunk moves as a rigid part during freestyle is tenable as the shoulders and hips roll to different extents and in some cases with different phase.
- In studies that shoulder and hip roll were calculated separately, methodological limitations and insufficient amount of reported data reduce the reliability and usefulness of the results.

- **Areas to be investigated**

The identified gaps in this area are as follows:

- No studies have examined the changes that might occur in shoulder and/or hip roll throughout the course of an event.
- The relationships between shoulder/hip roll and swimming V have not been studied adequately.
- Investigators have not explored the possibility of bilateral asymmetries in roll values and their association with swimming performance.

2.4.2.2 Kinematic parameters of the upper and lower extremity

- **Main findings of the existing research**

The MEF (during the UWP of the stroke) and MKF appear to be the main upper/lower extremity parameters associated with swimming performance. The review of the literature showed that:

- Faster freestyle and backstroke swimmers are characterised by higher MEF and MKF than slower swimmers.
- Swimmers of sprint events are characterised by more MKF than swimmers of distance events.
- A larger MKF appears to be beneficial as it gives the foot a larger ROM to produce propulsive forces.
- No other upper extremity kinematic parameters have been associated directly with swimming V.

- **Limitations of the existing research and areas to be investigated**

The influence of elbow/knee angular motion in swimming V has not been adequately studied, with important limitations reducing the accuracy and reliability of the reported data. Such limitations were: small number of cameras used; lack of information regarding statistical significance and meaningfulness, calibration procedures, error estimation and methods' reliability etc. In addition, no studies have calculated bilateral asymmetries in MEF/MKF values or the changes in these values throughout the course of an event.

2.4.3 Conclusion

The review of the scientific literature and the identified gaps/limitations underlined the need for advancement of the existing knowledge by employment of more sophisticated data collection/analysis methods that would enable the accurate and reliable investigation of freestyle kinematic parameters. Such methods should include among others: 3D data collection and analysis techniques; accurate anthropometric data; a large number of above and below water cameras that would increase the digitising accuracy; calibration of large volumes to minimise errors from extrapolations beyond these volumes etc.

With respect to the kinematic parameters, the review of the literature emphasised the importance of the calculation of intracycle variations for the V of the CM. The examination of the V maxima/minima and the magnitude of V fluctuations and their association with performance (as indicated by average horizontal V) also appeared to be of great interest. Moreover, the understanding of freestyle swimming technique could be improved by exploring the association between performance and kinematic parameters of the trunk and the upper and lower extremity, such as: shoulder and hip roll, MEF and MKF. Finally, a clearer and more complete picture of swimming kinematics can be gained by the calculation of kinematic parameters for both the left and right sides and the examination of any relationships between bilateral asymmetries and performance.

3. Methods

3.1 Test protocol

3.1.1 Participants

The participants in this study were 11 British male freestyle swimmers of national and international level. The descriptive characteristics of the group [expressed as mean ± standard deviation (SD)] were as follows: age: 16.9 ± 1.1 years; stature: 180.3 ± 5.6 cm; body mass: 71.7 ± 5.9 kg. The personal best performance for the 200 m freestyle event tested in this study was 123.5 ± 5.6 sec. To ensure participants' anonymity, code numbers were used to replace their names for any individual references made throughout this thesis.

Swimmers participated in this test only if their fitness, health and training status were appropriate. If there were any concerns (from the investigator/ swimmer/ coach) regarding the above in a test date, the test would be postponed to a later date. For example, swimmers would not participate in the test during or following periods of under- and/or over- training, injury or illness.

To minimise any over-training effects on the test performance, swimmers and coaches were instructed to avoid any stressful training the days before the test day. Research has shown that caffeine might cause significant changes in performance (e.g. Collomp *et al.*, 1992; MacIntosh & Wright, 1995). Therefore swimmers were instructed to abstain from food and beverages containing caffeine, as well as alcohol, and to follow a normal high carbohydrate/low fat diet, the days before and on the testing day. The level and experience of the participants in this study ensured that they had a sound knowledge and understanding of nutritional and hydration aspects. Further discussions with the participants and their coaches confirmed that the swimmers were adequately hydrated prior to and during the test day.

Due to the nature of the data collection in this study (video recordings of the swimmers' performance) and to the fact that all the tests were carried out in a safe, controlled pool environment, the ethical and risk considerations were minimal. The test procedures were approved by the University of Edinburgh Ethics Committee. Tests requiring maximum effort from participants involve a risk of possible muscular injuries. However, considering that the participants were national and international level swimmers and, therefore, hard training and performing in maximal effort was part of their daily training routine, the possibility of any muscular injuries occurring was considered negligible. Prior to the test date, all participants were given an information sheet (Appendix B) explaining the procedure of the experiment, including possible risks and anticipated benefits from the analysis of the data and feedback of the findings. The form was written in non-scientific language to be easily understandable by the participants. On the testing day the investigator explained to each participant all the procedural details and responded to any questions and concerns. Before the start of the test, each swimmer participating in the study was asked to sign an informed consent form (Appendix B).

3.1.2 Swimming test

Swimmers performed a 200 m freestyle swim with maximum effort. Each swimmer performed a personalised warm up before the test. This warm up consisted of low to moderate intensity aerobic swimming, with elements of kick and drills, as well as short race pace sets totalling approximately 1000 m.

Swimmers were asked to perform the 200 m maximum freestyle swim using their exact competition pacing and strategy. A push start was used instead of a dive start to eliminate any influence of the dive on the kinematics of the SC analysed for the first length. To ensure that the test performance would be at a level similar to competition performance, taking into consideration the effect of the use of the push start on the final time, a test would be considered acceptable if a swimmer's time for the 200 m was less than 105 % of his personal best performance of the season. If this was not achieved, the test would be repeated on a different day.

Research has shown that the breathing action in freestyle swimming might affect kinematic parameters such as intracycle V and body roll (e.g. Payton *et al.*, 1999b). Such differences would be expected to vary between, and possibly within swimmers, complicating any comparisons between and within SCs. To eliminate the effect of breathing on kinematic parameters, swimmers were instructed to avoid breathing while swimming through the pre-calibrated space (once for each 50 m). Considering the level and swimming experience of the participants, similar breathing restrictions were common practice in training and certain parts of competition events. Therefore, these breathing restrictions were not expected to alter the pacing strategy and/or kinematics of the 200 m swim. Nevertheless, for test-specific familiarisation purposes, swimmers were instructed to practise the non-breathing swimming through the pre-calibrated space during their warm-up.

3.2 Experimental set up for data collection

3.2.1 Camera set up

All tests were conducted in a six-lane, 25 m indoors pool at Edinburgh University, which was used exclusively by the investigator and the swimmers during all testing sessions. Each swimmer's performance was recorded with a total of six synchronised JVC KY32 CCD cameras. Four cameras were placed below and two cameras above the water. The camera operating frequency was 50 Hz and the shutter speed 1/120 seconds. The data for each camera were stored in digital format in separate hard drives, which were all connected to a main unit located in a poolside control room. All the camera functions (e.g. shutter speed, gain, zoom, focus, pan/tilt etc) were adjusted at the main unit.

Figure 3.1 illustrates the camera and calibration frame positions in the pool throughout the recordings (for details regarding the constructed calibration frame see section 3.2.2) and the directions of movement (as defined in this study). All cameras remained stationary during the recordings. The below water cameras were fixed at depths varying from 0.5 to 1.5 m under the water surface, to avoid errors due to the camera axes being in the same planes as the reference planes of the calibration frame. The above water cameras were fixed at a height between 2.5 to 3 m. The underwater cameras were approximately 8 m and the above water 12 m away from the centre of the calibrated space. The angle between the two above water camera axes was approximately 100°, while the angles between axes of adjacent below water cameras varied from approximately 75° to 110°. The camera settings were adjusted so that each camera recorded a space 6.5 m long, extending 1 m beyond each side the 4.5 m long calibration frame for the horizontal axis. The latter setting would ensure that at least one complete SC would be recorded and a large swimmer image would be available for data processing and digitising purposes. Figure 3.2 illustrates the field of view recorded by each one of the six cameras.

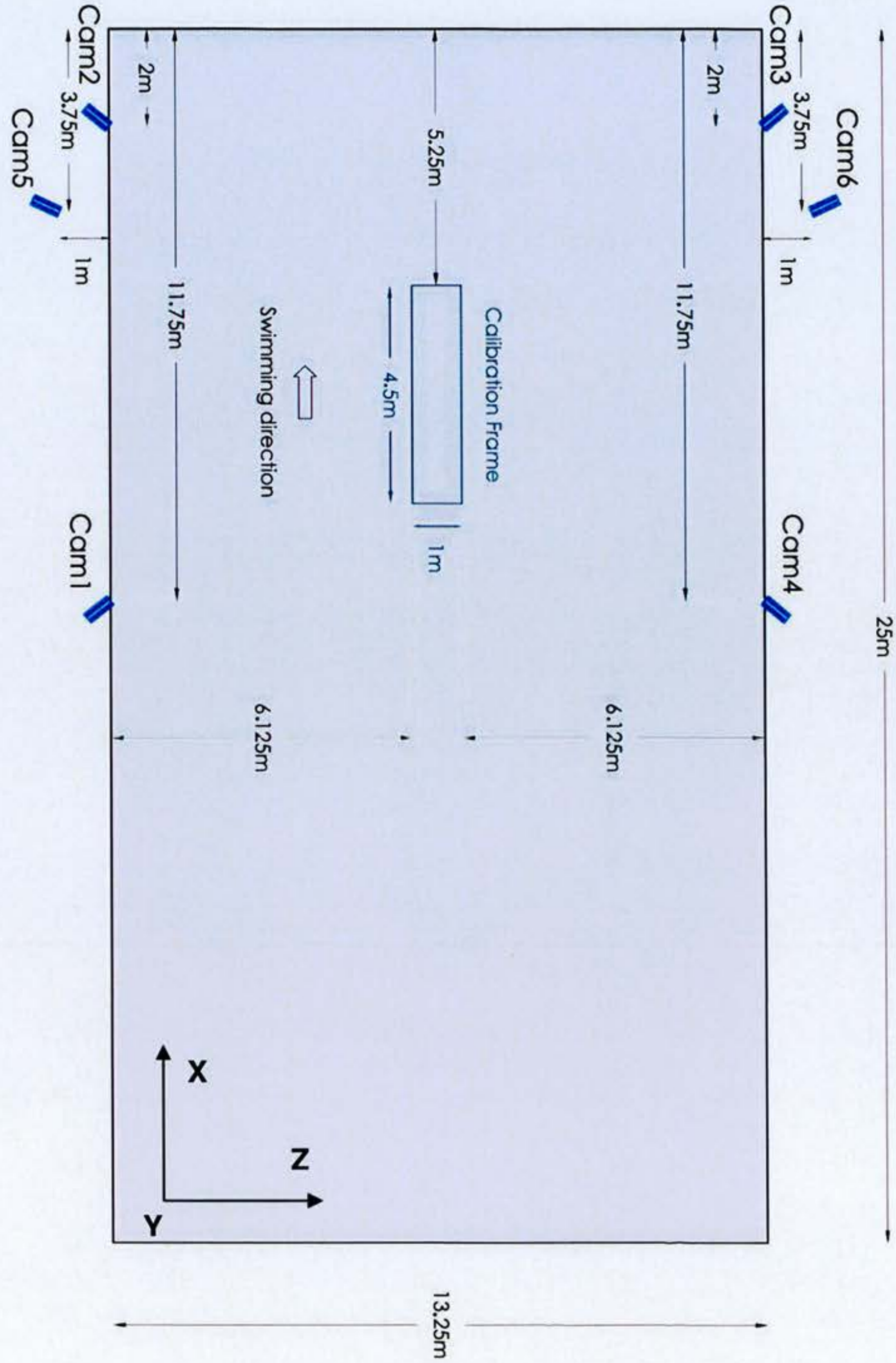

Figure 3.1: Camera and calibration frame set up used for 3D analysis
X / Y/ Z: Horizontal / Vertical / Lateral direction
(Below water: cameras 1 to 4; Above water: cameras 5 and 6)

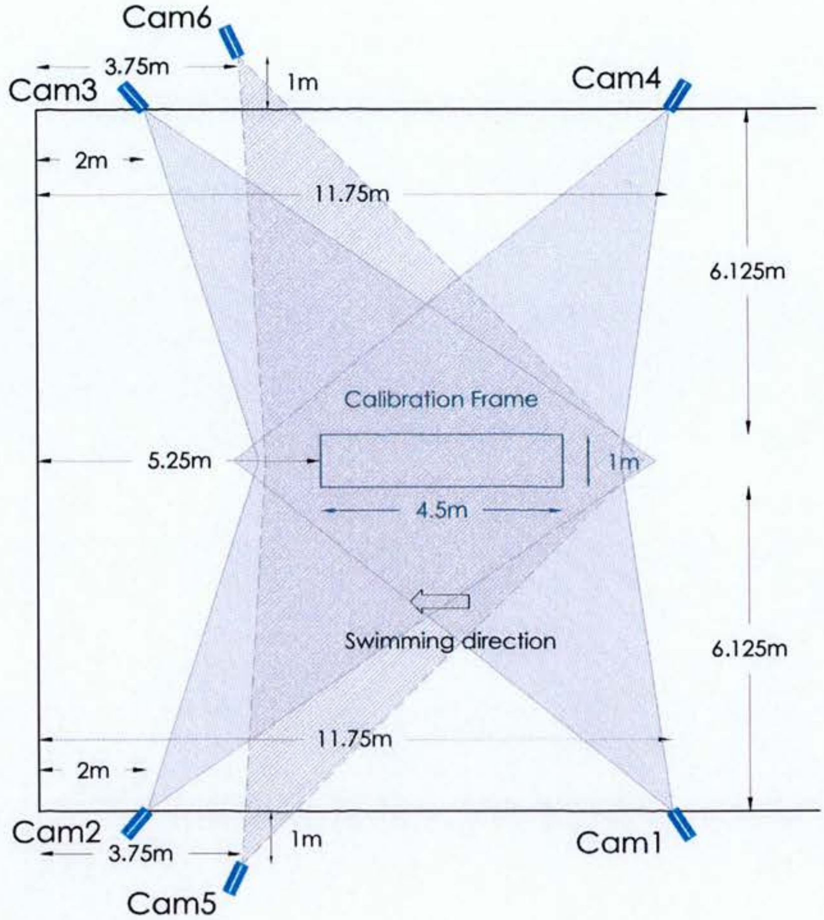

Figure 3.2: Cameras' field of view

(Below water: cameras 1 to 4; Above water: cameras 5 and 6)

3.2.2 Calibration

3.2.2.1 Calibration of the 3D space

Filming underwater is problematic and introduces errors additional to those associated with analyses of motion in air (Kwon, 1999). One of the pre-requisites for accurate quantification of the variables of interest is accurate calibration of the 3D space as part of the process of 3D coordinate reconstruction by the direct linear transformation (DLT) method. No calibration frame for 3D swimming analysis was available either at Edinburgh University or commercially. Therefore, the first project of this thesis was the construction of a calibration frame that would be used for the subsequent 3D swimming analysis. Furthermore, the accuracy and reliability of this frame for calculation of points in the space above and below water was calculated.

Preliminary data of this project were presented at the XIII International Symposium of Biomechanics in Sports (Beijing, China, 22-27 August 2005) and were published as a full paper in the conference proceedings (Psycharakis *et al.*, 2005). The full paper is presented in Appendix B.

Due to the limited number of 3D studies conducted in swimming, only a few papers reported 3D calibration frames used and their specifications. Cappaert *et al.* (1995; 1996) used a 5.6 m^3 calibration frame (2 x 2 x 1.4 m, for the X, Y and Z axes respectively). Payton *et al* (1999a; 2002) used a 1.1 m^3 (1.3 x 0.88 x 0.93 m) and Barbosa *et al.* (2003) a 9 m^3 (3 x 3 x 3 m) calibration frame. In all studies, similar to the present study, one SC was analysed. However, extrapolations beyond the calibrated space might cause inaccuracies (e.g. Challis, 1995). Therefore, one of the objectives of this project was to calibrate a space with sufficient length to minimise the possibility that parts of the SC would fall outside that calibrated space.

The constructed 3D calibration frame was a rectangular prism of 4.5 m length, 1.5 m height and 1m width, enabling the calibration of a space of 6.75 m^3 in total (Figure 3.3). All details regarding the construction process of this frame are presented in Appendix B (section: 'Construction process of the calibration frame').

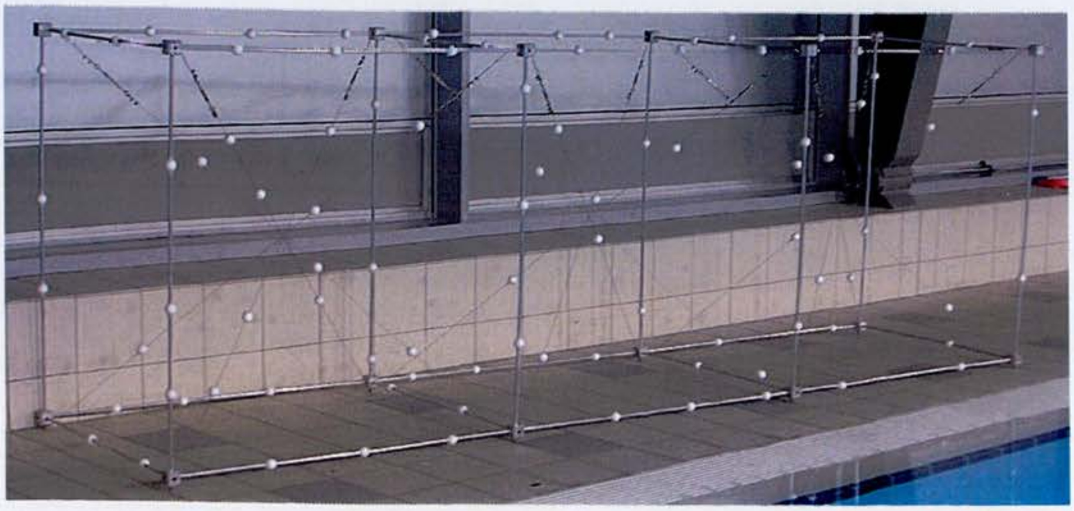

Figure 3.3: The calibration frame constructed for 3D analysis

Before each recording session, the calibration frame was placed into the swimming pool and monitored simultaneously by the four below and two above water cameras. The camera set up was identical to the one used for the subsequent recordings (as described in section 3.2.1 and shown in Figures 3.1 and 3.2). Following that, the calibration frame was removed from the pool, and each participant's performance was recorded while swimming through the pre-calibrated space. Figures 3.4 and 3.5 show a below and an above water view of the frame.

Figure 3.4: Below water view of the calibration frame

Figure 3.5: Above water view of the calibration frame

3.2.2.2 Accuracy and reliability of coordinate reconstruction

As discussed in the previous section, the accuracy and reliability of the calibration frame were assessed. The preliminary data presented at the XIII International Symposium of Biomechanics in Sports (Psycharakis *et al.*, 2005) as well as the extended analyses performed for the purposes of this thesis (section: 'Validation process of the calibration frame') are presented in Appendix B. Table 3.1 shows the mean differences (± SD) and RMS errors between the calculated and real coordinates (for X, Y and Z directions) for the 20 markers used for calibration in each view (below and above water).

Table 3.1: Mean values and root mean square (RMS) errors for the differences between calculated and real values for the coordinates of 3D calibration markers

Markers Location	**Mean Differences (±SD)** (mm)			**RMS errors** (mm)		
	X	**Y**	**Z**	**X**	**Y**	**Z**
Above water (N=20)	3.5 (±1.7)	3.3 (±1.8)	3.8 (±1.8)	3.9	3.8	4.2
Below water (N=20)	2.3 (±1.4)	2.4 (±1.5)	4.5 (±1.8)	3.3	3.6	5.2

The average RMS errors for both the above and below water points represented 0.1 %, 0.5 % and 0.5 % (0.4 % for the above water points) of the calibrated space for the X, Y and Z directions respectively. The digitising reliability indicated by 10 repeated digitisations of one marker (with the use of 10 control points) were ± 0.4 mm, ± 0.5 mm and ± 0.4 mm, for the X, Y and Z axes respectively.

The reconstruction accuracy and reliability in the present study was in general similar or better compared to other studies (for details of accuracy and reliability calculations in other studies see section 'Validation process of the calibration frame', Appendix B). In addition, the large volume of the calibrated space (6.75 m^3) minimised the possibility of extrapolation beyond that space, increasing further the accuracy of the measurements. Therefore, the errors in the system reconstruction accuracy and reliability in this study were considered to be low and acceptable.

3.2.3 Acquisition and calculation of anthropometric data

3.2.3.1 Elliptical zone method

The elliptical zone method maximises accuracy of CM calculation by taking into account the morphology of individual segments of individual subjects. A version of Jensen's (1978) elliptical zone method developed by Deffeyes and Sanders (2005, abbreviated from this point onwards as eZone) was used to calculate body segment parameter data for subsequent calculation of whole body CM. The Deffeyes and Sanders version was written in MATLAB for use on a PC.

3.2.3.2 Camera set up

Two digital Canon Ixus 400 cameras (4.0 mega pixels) were fixed to tripods, one for the side view and one for the front view of the participants. Even though 2 mega pixels digital cameras would be considered adequate for such calculations (Deffeyes & Sanders, 2005), the aforementioned higher resolution Canon cameras were preferred in order to allow for larger image-to-actual-body-size ratios and minimise errors during the digitising process. The camera axes were perpendicular to each other with the height of the centre of their lenses set to 1 m. To minimise image distortion, the cameras were positioned 12 m away from the participants with the maximum optical zoom (108 mm) being used to ensure large image sizes of the swimmers. The camera shutter speeds and apertures were set to 1/60 seconds and f5.5 respectively. The ISO equivalent speed of 200 was used. To optimise picture quality, the investigator ensured there was adequate lighting and the background provided sufficient contrast with the body segments.

3.2.3.3 Participant preparation

The participants wore the swimming suits and caps they used for the subsequent swimming test. The stature and body mass of the participants were then recorded with a use of a stadiometer (Seca 225-1821009) and a set of pre-calibrated laboratory scales (Seca 712-1321009). Black water-proof body paint was used to mark the participants' anatomical landmarks of interest for the eZone method and subsequent swimming test. These anatomical landmarks and the respective marker locations are shown in Table B.4 (Appendix B).

3.2.3.4 Filming procedures

Before photographing the participants, a reference scale of known distances of both the vertical and horizontal axes was photographed with both cameras and served as a calibration (Figure 3.6). The scale was placed at the same plane as the participants' mid-frontal and mid-saggital planes would be positioned for the subsequent pictures. The reference frame was then removed and the participant stood at the same point, adopting the anatomical reference position.

Figure 3.6: Side view of the calibration scale used for eZone calculations

Swimmers were instructed to adopt the anatomical reference position with feet plantar flexed, the neck slightly extended with the jaw parallel to the ground and the palms facing forwards with the fingers straight. Inclined blocks were used to facilitate plantar flexion of the feet without bending the toes. Each swimmer was photographed from the frontal and lateral views simultaneously. Figure 3.7 shows a front and a side view picture of participants tested in this study.

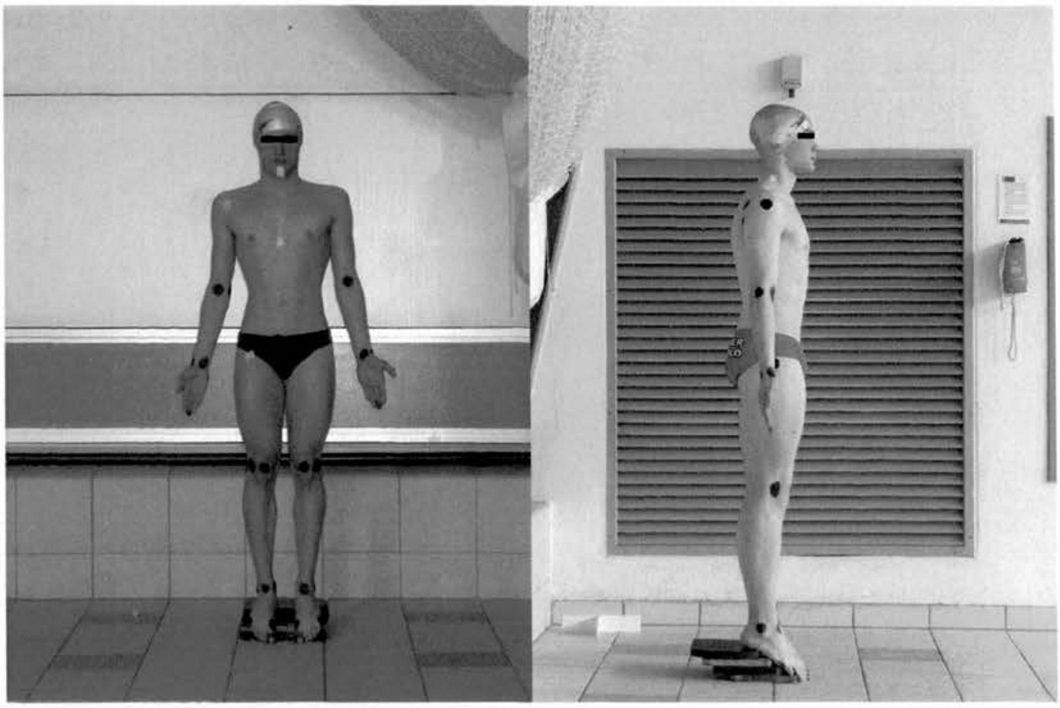

Figure 3.7: Front and side view pictures of participants, used for eZone calculations

3.2.3.5 Mass and centre of mass calculation

The pictures of the reference scale and the participants were saved as 'jpeg' files and input to the MATLAB eZone programme running on a PC. Research has shown that large image-to-actual-body-size ratios tend to reduce the mean digitising errors (Wicke & Lopers, 2003). Therefore, for all digitising operations the images were zoomed in to ensure sizes of a 1:5 ratio or larger.

In response to the prompts from the eZone programme the operator digitised the reference scale and all the anatomical landmarks for each swimmer (as shown in Table B.4, Appendix B) in both views. Then, the outlines of the following segments were digitised for each view: head and neck; trunk (thorax and abdomen); upper limb (upper arm, forearm and hand); lower limb (thigh, shank and foot). Figure 3.8 shows the front and side views of the model displayed in eZone upon completion of the digitising process.

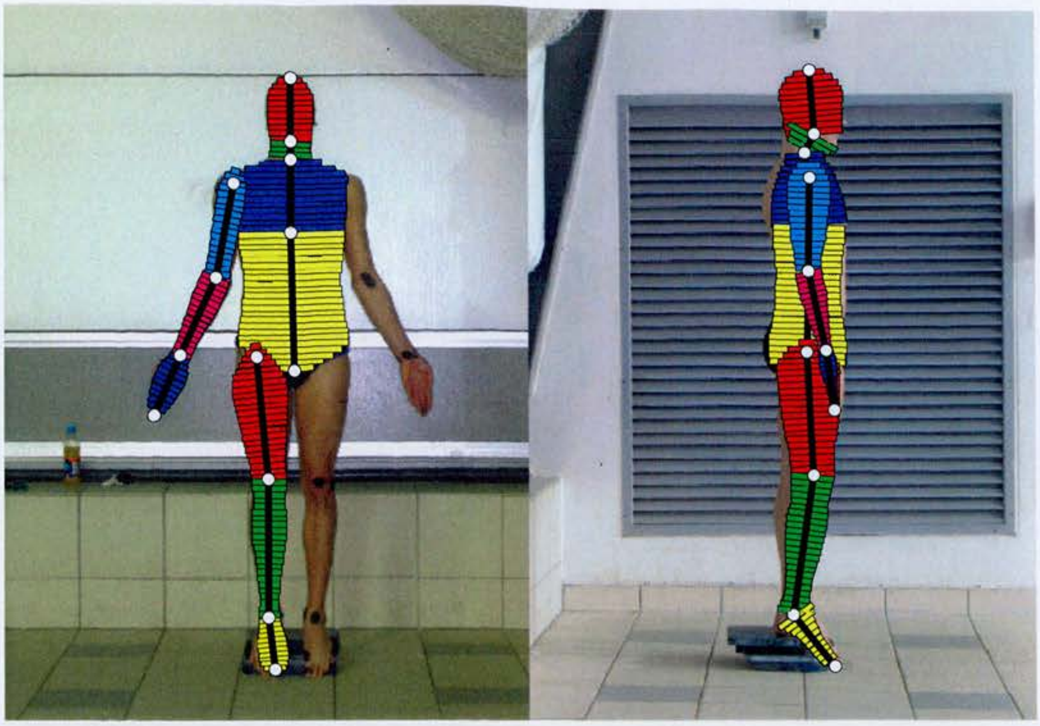

Figure 3.8: Front and side views of the model displayed in eZone programme upon completion of the digitising process

Note: These models only served as operator's confirmation references and did not perfectly represent the participants' calculated anthropometric data

3.2.3.6 Accuracy and reliability of eZone method

As an indication of accuracy, the differences between the obtained (calculated with eZone) and real (measured with the use of pre-calibrated laboratory scales) body mass values were calculated for all 11 participants. The mean and SD of the values, as well as the percentages of the mean differences were then calculated. In addition, similar to the accuracy calculations conducted for the 3D calibration frame, the RMS errors were calculated, as they provide a rigorous assessment of accuracy (Challis, 1997). Moreover, this measure represents the error bounds within which 68 % of measures would fall and is the combined effect of accuracy and reliability. The RMS errors were calculated by squaring the errors for all participants, and then taking the square root of the average of the squares of the errors.

The mean (±SD) differences (for the group of swimmers) between calculated and real values for the whole body mass were -0.2 ± 0.9 kg or -0.3 ± 1.3 % (expressed as percentage of the real body mass values). The RMS errors for the absolute and percentage differences were respectively 0.9 kg and 1.3 %. The mean errors and SD of the errors found in this study were in general smaller than those reported in most studies in which the eZone method has been used (Jensen, 1978; Finch, 1985; Yokoi *et al.*, 1985; Jensen, 1986a; 1986b; Sanders *et al.*, 1991; Jensen & Fletcher, 1994), indicating that the eZone method used in this study had high accuracy. The mean errors reported in other studies ranged from 0.1 ± 3.0 % (Jensen & Fletcher, 1994, N=19) to 1.4 ± 0.4 % (Jensen, 1978, N=3).

Reliability of the eZone calculations and the digitising procedure was assessed by repeated digitising of the same participant. The same operator (to eliminate inter-operator errors and to use the same operator as in the data analysis of the thesis) repeated the procedure 10 times. The SD for the body mass values across all digitisations was calculated as an indication of reliability.

The reliability calculations indicated low SD values for both the body mass calculations and the differences between calculated and real body mass values. The SD for the whole body mass was 0.4 kg, which represented 0.3 % of the mean mass value of this participant. These values were considered low and acceptable. However, no other studies have reported digitising reliability for the eZone method.

3.3 Data treatment and analysis

3.3.1 Selection of stroke cycles and analysis parameters

To address the purposes of this study the following kinematic variables were analysed for all participants:

- Intracycle V of the CM, for the horizontal, lateral and vertical directions.
- Trunk kinematics: shoulder and hip roll.
- Upper and lower extremity kinematics: MEF during the underwater arm phase of the stroke; MKF.

In addition to the above, the generic kinematic parameters that describe performance were calculated for each SC. These were the average V, SR, SL and time for each SC. Calculation methods for all the aforementioned variables are presented in section 3.3.3.

Swimmers were monitored while swimming through the pre-calibrated space and one complete SC was analysed for each 50 m of the 200 m freestyle. The SCs recorded were those for which swimmers were swimming in the direction shown in Figure 3.1, to eliminate any influence of the turns and underwater swimming on stroke kinematics. A SC was defined as the period between and including the video field corresponding to hand entry to the video field corresponding to the next hand entry of the same hand.

3.3.2 Digitising procedure

The Ariel Performance Analysis System (APAS) was used to digitise the body landmarks for each field during the period of interest and for each camera view and to calculate the 3D coordinates of each body landmark. The calculation of 3D coordinates relies on the Direct Linear Transformation (DLT) method (Abdel-Aziz & Karara, 1971) incorporated in the APAS software. The accuracy of locating submerged markers was maximised by having four cameras. This meant that for the vast majority of the digitised frames each marker was clearly visible by at least two different cameras, minimising the incidence of 'guessed points' being used in the DLT calculation.

Prior to digitising, the synchronised files obtained for all six cameras were trimmed to the SCs of interest, using the APAS 'Trim' software function. Accurate trimming was ensured by using the time codes displayed on the top left corner of each camera frame (e.g. see Figure 3.4). Two sequence files were then created in the APAS 'Digitise' software function, one for the below and one for the above water views. For all the recorded frames in the SC and for each camera, the following reference points were manually digitised for each swimmer: vertex; shoulder, elbow, wrist, hip, knee, ankle and metaphalangeal joints; the end of the middle fingers and the big toes. These were the same anatomical reference points marked and digitised during the data collection for the eZone method. For each camera, all the visible points were digitised for each frame. APAS software allows skipping non-visible points, rather than having to digitise an estimated point on the screen. For subsequent transformations, APAS uses only the input data for the digitised points for each camera.

The number of calibration points to be used was based on the results of the accuracy comparison between different numbers of control points, as described in

Appendix B (section: 'Validation process of the calibration frame'). The calibration frame position (described in section 3.2.2.1) allowed the use of coordinates from the same reference system for both below and above water views. This eliminated the need for adjustments in the raw data obtained for all body landmarks digitised on each swimmer.

When digitising was completed, the above and below water sequences were separately transformed into 3D coordinates using the APAS 'Transform' function based on the method of Abdel-Aziz and Karara (1971). The raw displacement data for all the digitised landmarks and for both views was then obtained in the APAS 'Display' software function. The above and below water data were then combined into a single file representing the continuous coordinates throughout the SC for each landmark and saved in 'text' files. These data were used for the calculation of the parameters of interest as described in section 3.3.3.

3.3.3 Calculation of variables

A MATLAB programme developed by Sanders (2005) was used for all variable calculations in this study. The investigator input the text files with the anthropometric (as described in section 3.2.3) and raw displacement data for all the landmarks of interest (as described in section 3.3.2) for each SC and each swimmer. A Fourier transform and inverse transform were used to filter and smooth the data by retaining harmonics at 6 Hz in the inverse transform. For swimming movements, smoothing frequencies of 6 Hz or less are considered acceptable and are commonly used by researchers (e.g. Cappaert *et al.*, 1995; Payton *et al.*, 2002). Data were output as 101 points representing percent points (0 to 100) of the SC by setting the loop size to 101 in the inverse Fourier transforms. Real time values corresponding to the percent points were also calculated and output.

All the parameters presented below were calculated four times (once for each recorded SC) during the 200 m freestyle test, to allow for within as well as between participant analyses of the variable. Mean values for each parameter of interest in each SC were calculated by adding the scores for all swimmers and dividing by the number of swimmers. Mean 200 m values were also calculated by adding the mean group values for the four SCs and dividing by four. Finally, the values and variation for each kinematic parameter of interest were examined in relation to average V of the CM throughout the 200 m.

- **Intracycle velocity and velocity fluctuation**

The CM displacement (cm) was determined by the standard procedure of summing moments of the segment centres of mass about the X, Y, and Z reference axes. The V of the CM ($m \cdot sec^{-1}$) was then obtained by differentiating the CM displacement data using the first central difference formula. The distinct minimum and maximum instantaneous velocities were obtained from the intracycle V data. The timings of V maxima/minima in each SC were calculated as a percentage of the overall SC time. The fluctuation of the CM velocities ($m \cdot sec^{-1}$) in each direction was calculated by subtracting the minimum from the maximum instantaneous V in each SC. Finally, the V fluctuation for each direction was also calculated as a percentage of the average horizontal V of the CM.

- **Average velocity, stroke rate and stroke length**

The average horizontal swimming V ($m \cdot sec^{-1}$) for each swimmer was calculated by taking the mean of the CM horizontal V for one complete SC. SR ($cycles \cdot min^{-1}$) was calculated by dividing one (representing one complete SC) with the time (in minutes) required to complete a given SC. Finally, SL ($m \cdot cycle^{-1}$) was calculated by dividing the horizontal displacement of the CM during a SC by one (representing one complete SC).

- **Shoulder and hip roll**

The trunk vector was defined by connecting a line from the midpoint of the shoulder to the midpoint of the hip joints. The normal to the shoulder/trunk plane was defined as the cross product of the trunk unit vector and the unit vector in the direction of the line connecting the shoulder joints. The shoulder roll angle (degrees) was calculated as the angle between the vertical and the projection of the normal onto the YZ plane. The hip roll angle (degrees) was calculated in the same manner as the shoulder roll except that the normal to the hip/trunk plane rather than the normal to the shoulder/trunk plane was projected onto the YZ plane. The unit vector representing the line of the hips was in the direction of the line joining the hip axes.

The peak shoulder and hip roll to each side were calculated to identify possible technique asymmetries. Rolling to the right was defined as the rolling of the shoulders/hips during the phase of the stroke that the right shoulder/hip was higher than the left shoulder/hip, and vice-versa. Timings of appearance of peak shoulder and hip roll angles were calculated for both sides as a percentage of the overall SC time.

- **Angular motion of the elbow and knee joints**

The elbow angular displacement (degrees) was calculated as the arctangent of the dot product of the unit vectors of the lines connecting the shoulder and elbow joints and the elbow and wrist joints. Similarly, the knee angle (degrees) was calculated as the arctangent of the dot product of the unit vectors of the lines connecting the hip and knee joints and the knee and ankle joints. Both angles were calculated separately for the left and right elbow/knee joints. The MEF and MKF corresponded to the minimum elbow (during the UWP) and knee angles, respectively. The timing of MEF during the underwater phase of the stroke was calculated for both arms as a percentage of the overall SC time. Similarly, the timing of MKF in a SC was calculated for both knees as a percentage of the overall SC time.

- **Criteria for bilateral analyses of kinematic parameters**

As discussed above, all kinematic parameters in this study were calculated for both right and left sides to identify any bilateral asymmetries in swimmers' techniques and to examine whether the magnitude of any asymmetries was associated with swimming V. The investigation of the cause of any asymmetries was beyond the scope of this thesis and, therefore, the research design did not include the measurement of any parameters that could be related to possible technique asymmetries. Nevertheless, personal communication with the swimmers and coaches throughout the testing period revealed that all swimmers tested were right handed. This meant that all swimmers favoured the right hand/arm for one-handed tasks (e.g. writing) as they felt it was superior to the left in terms of strength and co-ordination.

In view of this fact and in addition to the analysis of the overall bilateral asymmetries (absolute values), it was decided to compare the values of the right and left sides. The latter would allow the identification of any side dominance and the extent to which any such dominance would be associated with the right-handedness of the swimmers.

- **Reliability of kinematic parameters calculation**

The influence of digitising reliability on the kinematic parameters measured in this study was assessed with the same methods used for assessment of digitising reliability of the calibration frame and eZone method. Thus, one complete SC of one swimmer was digitised 10 times for all six cameras (four below and two above water). For each parameter of interest, the SD across all digitisations was calculated as an indication of reliability.

3.3.4 Statistical analysis

The results for all variables were presented in graphs and tables for the whole group (mean values ± SD) as well as for some individual swimmers. To identify significance of changes in variables across the stages of the swim, repeated measures analysis of variance (ANOVA) was performed between SCs 1, 2, 3 and 4. Repeated measures ANOVAs were also used to address significance of the differences between scores of the left and right side for each parameter of interest. To assess the nature and strength of correlations between variables for each of the race stages, the Pearson's product moment correlation coefficient (r) was calculated. This meant that there were 11 scores (one for each participant) for each variable for each race stage (SCs 1 to 4 and mean 200 m scores). The exact p values were calculated and statistical significance was accepted for $p<.05$.

As one of the main statistical assumptions is that characteristics of the normal curve can be applied (Vincent, 2005), in all statistical calculations in this study skewness and kurtosis were assessed for each data set. Skewness is a description of the direction of the peak of the curve of distribution of data and the nature of the tails of the curve, while kurtosis is description of the shape of the curve of the distribution of data (Thomas *et al.*, 2005). According to Vincent (2005), data are considered to be within acceptable limits of skewness and kurtosis if the Z values (raw scores expressed in SD units) do not exceed ± 2.0. Since no data sets in this study violated the assumption of skewness and kurtosis, no data adjustments were required.

For all the repeated measures ANOVAs performed in this study, the assumption of sphericity was tested. Thomas *et al.* (2005) stated that in repeated measures designs the pooled data (across all participants) must exhibit sphericity (the assumption that repeated measures are uncorrelated and have equal variance). For the present study, the Greenhouse-Geisser adjustment was applied for correction of the values when the sphericity assumption was violated (Vincent, 2005).

In addition to the original repeated measures ANOVA for the four SCs, post hoc tests were conducted to identify the significance of the findings for different pairs of SCs. However, further statistical measurements increase the probability of type I errors (differences found that in reality do not exist). To eliminate the possibility of type I errors, a Bonferroni adjustment to reduce the alpha level was applied, as described by Vincent (2005).

All ANOVA measurements, as well as the tests for data skewness and kurtosis and sphericity, were conducted with the use of the Statistical Package for Social Sciences (SPSS) 14.0 software. The Microsoft Office Excel 2003 software was used for the calculations of Pearson's correlation coefficient.

4. Results

4.1 Reliability of kinematic parameters calculation

Table 4.1 shows the reliability calculations for each kinematic parameter of interest. The values were in general low and acceptable, indicating reliable 3D data calculations in this study.

Table 4.1: Reliability of kinematic parameters

Parameter	Standard Deviation
Average horizontal V (m·sec^{-1})	0.002
Stroke rate (cycles·min^{-1})	0.002
Stroke length (m·cycle^{-1})	0.00
Maximum/minimum horizontal V (m·sec^{-1})	0.03
Timing of maximum/minimum horizontal V (% of SC time)	1.29
Horizontal V Fluctuation (m·sec^{-1})	0.03
% Horizontal V fluctuation (% of average V)	1.59
Vertical V fluctuation (m·sec^{-1})	0.02
% Vertical V fluctuation (% of average V)	1.42
Lateral V fluctuation (m·sec^{-1})	0.03
% Lateral V fluctuation (% of average V)	1.70
Shoulder roll (degrees)	2.40
Hip roll (degrees)	2.00
Timing of shoulder/hip maximum roll (% of SC time)	1.12
Maximum elbow flexion (degrees)	2.23
Timing of maximum elbow flexion (% of SC time)	0.55
Maximum knee flexion (degrees)	1.69
Timing of maximum knee flexion (% of SC time)	1.33

4.2 Average velocity, stroke rate and stroke length

One of the conditions for considering a test acceptable was that a swimmer's performance would be less than 105 % of his personal best time of the season. Since all swimmers' performance satisfied these criteria when first tested, no swimmers had to repeat the test on a different day. Swimmers were 2.0 ± 2.9 % slower than their best performance of the season. The relatively high SD was due to the fact that some swimmers' performances were faster than their season's best.

Figure 4.1 illustrates the average horizontal V of the CM, for each swimmer and for all four SCs of the 200 m freestyle (numerical data are shown in Table C.1, Appendix C). Table 4.2 shows the changes in SR, SL and time of the SC throughout the 200 m (individual data are shown in Table C.2, Appendix C). Table 4.3 shows the significance levels obtained from the repeated measures ANOVA performed for V, SR, SL and time.

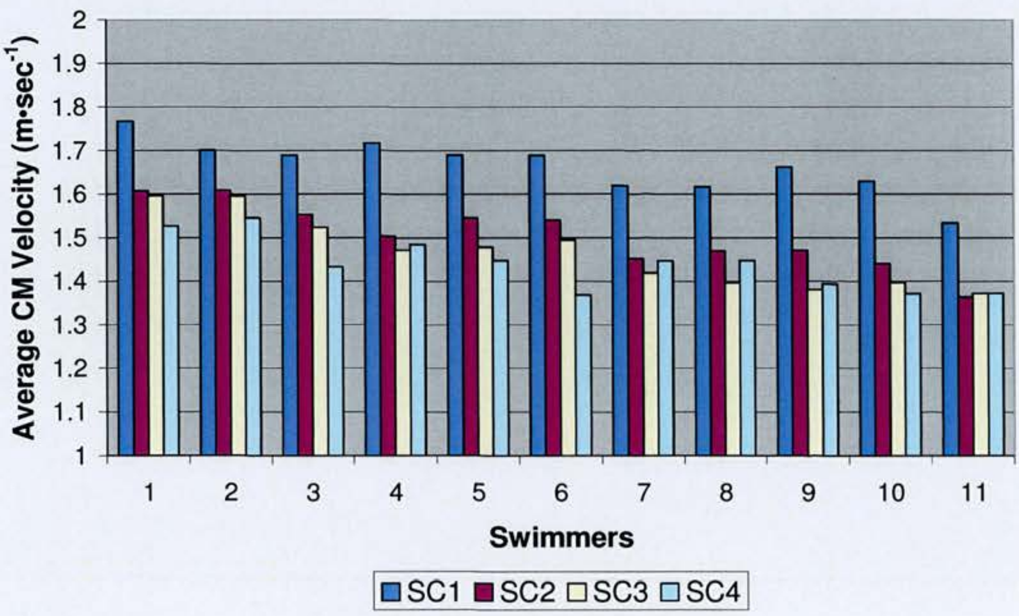

Figure 4.1: Average horizontal V of the CM for all swimmers

Table 4.2: Stroke rate, stroke length and time of each SC

	SC1	SC2	SC3	SC4	Mean
Stroke Rate	47.79	42.85	44.04	43.39	44.52
(cycles·min^{-1})	(±5.37)	(±5.69)	(±5.41)	(±4.74)	(±4.84)
Stroke Length	2.11	2.14	2.02	2.01	2.07
(m·cycle^{-1})	(±0.24)	(±0.28)	(±0.28)	(±0.22)	(±0.24)
Stroke Cycle Time	1.27	1.42	1.39	1.40	1.37
(sec)	(±0.15)	(±0.20)	(±0.21)	(±0.17)	(±0.17)

Table 4.3: Significance levels of the repeated measures ANOVA tests for average horizontal V, SC time, SR and SL

	Average V	Stroke Rate	Stroke Length	Time
Overall	$F_{3,30}$=104.5 (p<0.001)*	$F_{1.7,17}$=8.7 (p=0.004)*	$F_{1.5,15}$=4.0 (p=0.052)	$F_{3,30}$=8.0 (p<0.001)*
SC1 / SC2	<0.001*	<0.001*	1.000	<0.001*
SC1 / SC3	<0.001*	0.148	1.000	0.181
SC1 / SC4	<0.001*	<0.001*	0.005*	0.001*
SC2 / SC3	0.008*	1.000	0.506	1.000
SC2 / SC4	0.014*	1.000	0.008*	1.000
SC3 / SC4	0.808	1.000	1.000	1.000

*: significant at p<.05

In general, the average horizontal V of swimmers' CM decreased with each SC, with the exception of SC4, where some swimmers increased V in relation to SC3. The average horizontal V was significantly higher in SC1 than in the other three SCs. Horizontal V was also significantly higher in SC2 than SC3 and SC4. The mean V for the group throughout the 200 m was 1.52 ± 0.06 m·sec^{-1}.

The reduction in horizontal V from SC1 to SC4 was 0.23 ± 0.05 m·sec^{-1}. When expressed as a percentage of the initial average V (V for SC1), the V reduction was 13.50 ± 3.03 %. The correlation between the mean 200 m horizontal V and the reduction in horizontal V (V for SC1 minus V for SC4) was very low and not significant (r=0.11, p=0.748). Similarly, there was a very low correlation (r=-0.01, p=0.977) between mean 200 m V and the V reduction expressed as a percentage of the initial V.

SR was significantly higher and SC time was significantly lower in SC1 than in SC2 and SC4. SL was significantly lower in SC4 than in SC1 and SC2. The lack of significant differences between SC1 and SC3 in all parameters was probably due to variability in the SR/SL combinations used by some swimmers.

There was no significant correlation between V and SR ($0.23 \leq r \leq 0.42$, $0.198 \leq p \leq 0.496$) or V and SL ($-0.10 \leq r \leq 0.09$, $0.779 \leq p \leq 0.977$) throughout the test. However, SR and SL were significantly correlated for all SCs and the mean 200 m values ($-0.95 \leq r \leq -0.91$, p<0.001).

4.3 Intracycle velocity of the centre of mass

4.3.1 Horizontal velocity

4.3.1.1 Velocity patterns

The intracycle horizontal V of the CM varied greatly both within and between swimmer SCs. There were two distinct V maxima for all SCs for each swimmer, associated with the left and the right underwater arm phases. There were two distinct V minima associated with the underwater arm phases for most swimmers. In some cases, instantaneous V values similar in magnitude to these minima existed in other parts of the SC (e.g. see Figure 4.2, SC4, second V trough).

The V profiles of most swimmers indicated bilateral asymmetries for both maximum and minimum values in each SC, with the magnitude of difference between sides varying between swimmers and occasionally across cycles within swimmers. The magnitude of V maxima/minima and their timing of appearance in each SC are presented in sections 4.3.1.3 and 4.3.1.4. Figures 4.2 and 4.3 illustrate the horizontal V patterns of the CM for the swimmer with the most symmetrical and the swimmer with the most asymmetrical maximum V pattern.

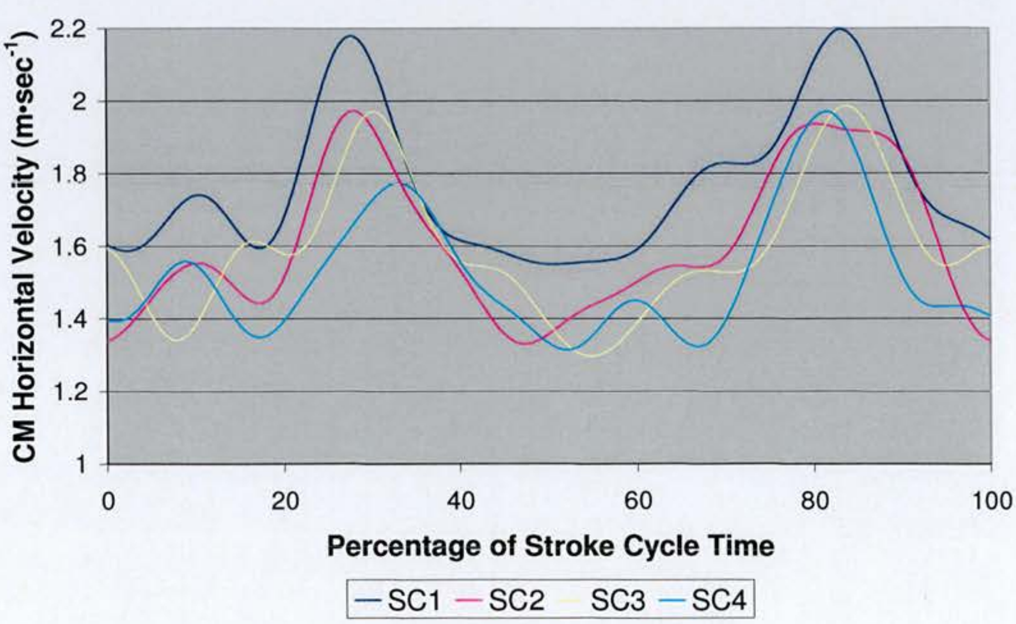

Figure 4.2: Pattern of horizontal V of the CM for swimmer 1

The pattern is symmetrical with regard to the magnitude of the two V maxima

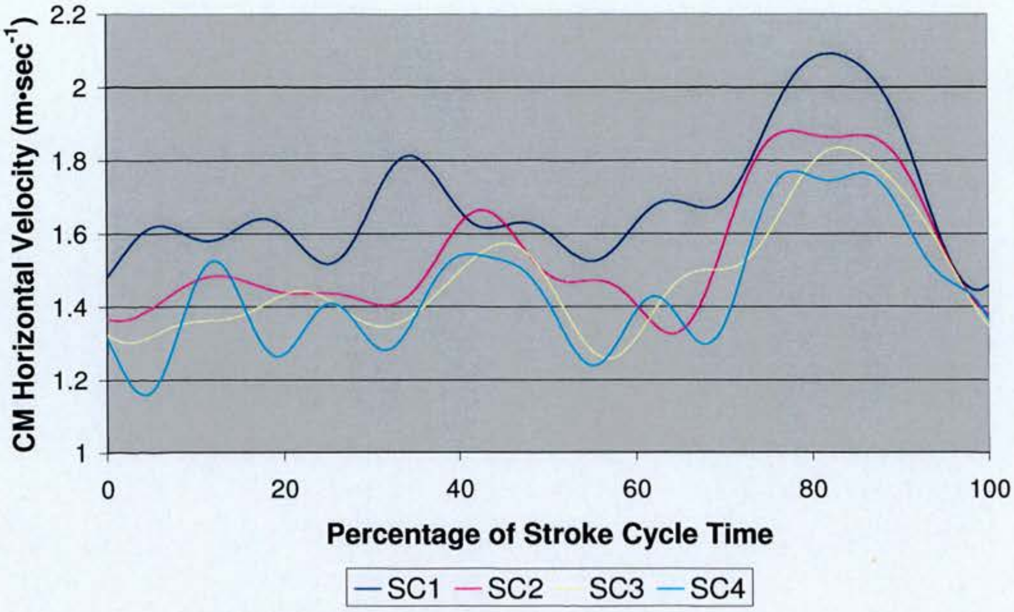

Figure 4.3: Pattern of horizontal V of the CM for swimmer 5

The pattern is not symmetrical with regard to the magnitude of the two V maxima

4.3.1.2 Velocity fluctuations

Figure 4.4 shows the magnitude of intracycle horizontal V fluctuations (absolute and percentage) for the group of swimmers for each SC (individual swimmer data are shown in Table C.3, Appendix C). Figure 4.5 shows the changes in overall maximum and minimum V throughout the test. Table 4.4 shows the significance levels obtained from the repeated measures ANOVA performed for absolute and percentage fluctuations and maximum/minimum V.

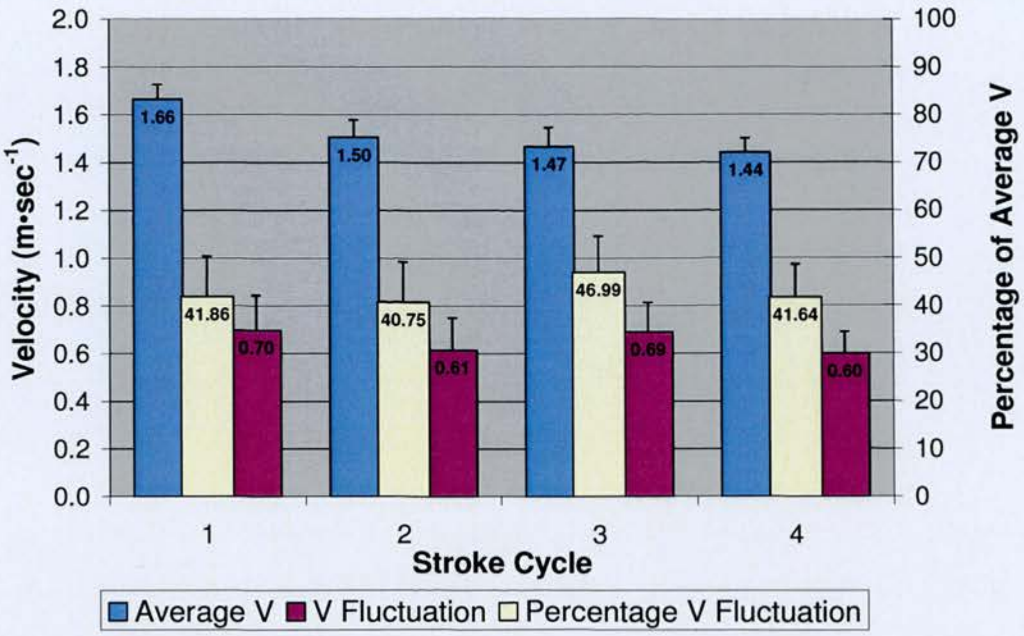

Figure 4.4: Magnitude of intracycle fluctuations of the horizontal V of the CM

Values in the left y-axis represent average V and V fluctuation. Values in the right y-axis represent percentage V fluctuation.

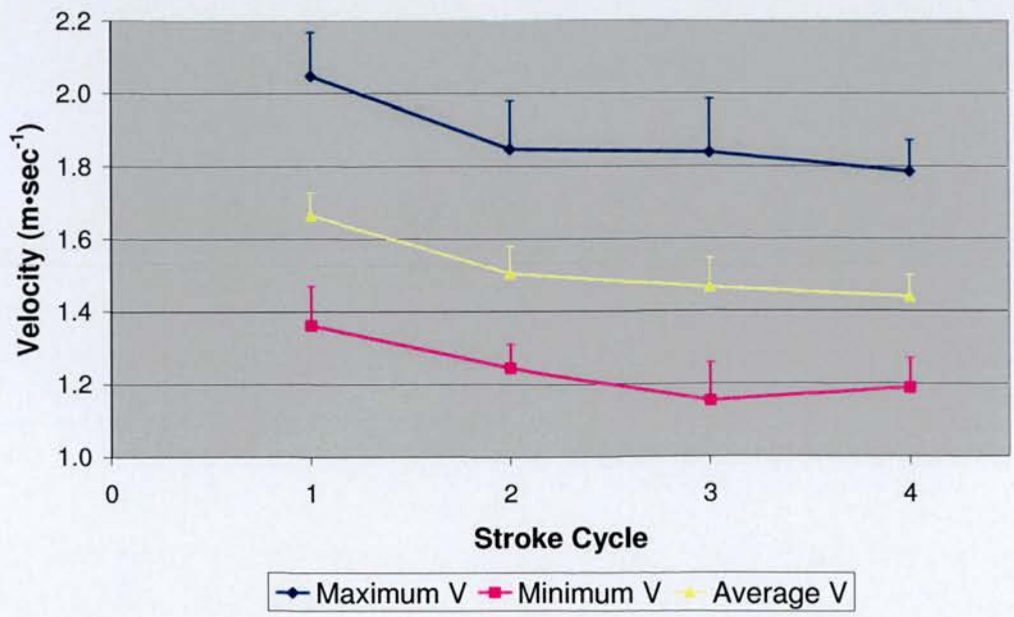

Figure 4.5: Minimum and maximum intracycle horizontal V of the CM

Table 4.4: Significance levels of the repeated measures ANOVA tests for horizontal V fluctuations and minimum/maximum V of the CM

	V Fluctuations		Instantaneous V	
	Absolute	**%**	**Maximum**	**Minimum**
Overall	$F_{3,30}$=6.2 (p=0.002)*	$F_{3,30}$=4.8 (p=0.008)*	$F_{2,20}$=35.2 (p<0.001)*	$F_{3,30}$=29.0 (p<0.001)*
SC1 / SC2	0.087	1.000	<0.001*	0.002*
SC1 / SC3	1.000	0.265	0.001*	<0.001*
SC1 / SC4	0.145	1.000	<0.001*	0.001*
SC2 / SC3	0.044*	0.017*	1.000	0.004*
SC2 / SC4	1.000	1.000	0.223	0.166
SC3 / SC4	0.005*	0.009*	0.443	1.000

*: significant at p<.05

The absolute and percentage fluctuation values were significantly higher in SC3 than SC2 and SC4. There were no significant differences in V fluctuations for any other pairs of SCs. The percentage fluctuation values were similar in SC1, SC2 and SC4 (differences smaller than the reliability calculations shown in Table 4.1, section 4.1). The data also showed between and within swimmer differences in fluctuation values for a given average V.

The maximum/minimum velocities were significantly higher in SC1 than in the other three SCs. There were no significant differences in maximum/minimum V for any other pairs of SCs, with the exception of minimum V that decreased significantly from SC2 to SC3.

Table 4.5 shows the correlations between average V of the CM and the following variables: maximum/minimum V, absolute/percentage fluctuation of V. There were no significant correlations between the average horizontal V and the magnitude of V fluctuation. Average V was significantly correlated with maximum V. The correlations with the minimum V for the same phases were either lower or not significant (with the exception of SC4).

Table 4.6 shows the correlations between maximum/minimum V and absolute/percentage V fluctuation. Maximum V was significantly correlated with both the absolute (with the exception of SC4) and percentage (with the exception of

SC3 and SC4) V fluctuation. Minimum V was significantly correlated only with the percentage fluctuations in SC1 and SC4. Finally, the correlations between maximum and minimum V were not significant ($0.15 \leq r \leq 0.56$, $0.080 \leq p \leq 0.660$).

Table 4.5: Correlations between average V of the CM and the following variables: maximum/minimum V, absolute/percentage V fluctuation

	Correlations with Average V				
	SC1	**SC2**	**SC3**	**SC4**	**Mean**
V Fluctuation	0.29 (0.387)	0.42 (0.198)	0.43 (0.187)	-0.07 (0.838)	0.34 (0.306)
% V Fluctuation	0.14 (0.681)	0.20 (0.555)	0.13 (0.703)	-0.34 (0.306)	0.10 (0.770)
Maximum V	0.79 (0.004)*	0.80 (0.003)*	0.86 (<0.001)*	0.71 (0.014)*	0.81 (0.003)*
Minimum V	0.49 (0.126)	0.58 (0.061)	0.72 (0.013)*	0.83 (0.002)*	0.64 (0.034)*

p values are shown in the parentheses
*: significant at p<.05

Table 4.6: Correlations between maximum/minimum V and absolute/percentage V fluctuation

	Correlations with Absolute V Fluctuation				
	SC1	**SC2**	**SC3**	**SC4**	**Mean**
VMax	0.71 (0.014)*	0.85 (<0.001)*	0.72 (0.013)*	0.56 (0.073)	0.75 (0.008)*
VMin	-0.58 (0.061)	-0.33 (0.322)	-0.16 (0.638)	-0.50 (0.117)	-0.37 (0.263)
	Correlations with % V Fluctuation				
	SC1	**SC2**	**SC3**	**SC4**	**Mean**
VMax	0.61 (0.046)*	0.72 (0.013)*	0.50 (0.117)	0.34 (0.306)	0.60 (0.050)*
VMin	-0.68 (0.021)*	-0.50 (0.117)	-0.42 (0.198)	-0.70 (0.017)*	-0.55 (0.080)

p values are shown in the parentheses
*: significant at p<.05

4.3.1.3 Analysis of velocity fluctuations for the underwater phases of the left and right arms

4.3.1.3.1 Appearance of distinct maxima and minima

Both the minimum and maximum velocities for each arm's UWP were observed when the opposite arm was not contributing to propulsion. In the case of every swimmer, maximum V occurred during the first half of the UWP of the arm (after performing the 'catch'), while the hand was moving downwards and backwards (elbow ahead of shoulder on the horizontal axis). At the same time the opposite arm was above water, at the early stages of the recovery phase. Minimum V occurred at the second half of the UWP of the arm, when the hand was moving backwards and upwards (elbow behind the shoulder on the horizontal axis). During the appearance of minimum V the opposite arm was either at the end of the recovery phase (before entering the water) or at the glide phase of the UWP (hand gliding forward without applying any propulsive forces), before performing the 'catch'.

4.3.1.3.2 Changes throughout the test

Figure 4.6 illustrates the V maxima/minima and the V fluctuations during the UWP of each arm (numerical data are shown in Tables C.4 to C.7, Appendix C).

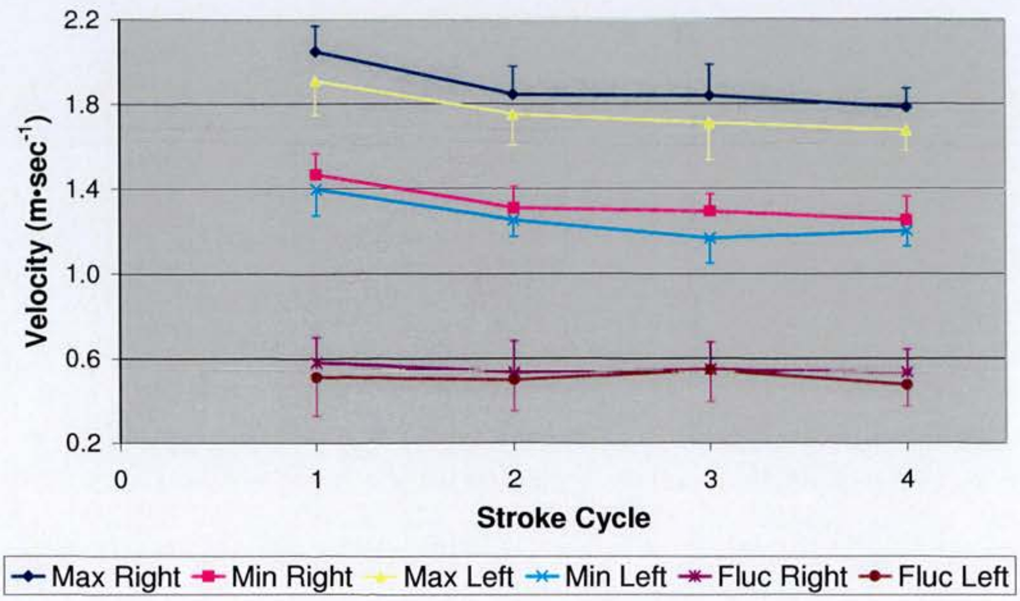

Figure 4.6: Minimum (Min) and maximum (Max) instantaneous V and magnitude of V fluctuations (Fluc) corresponding to the UWP of the left and right arms

Table 4.7 shows the significance levels obtained from the repeated measures ANOVA performed for the V maxima/minima and V fluctuations for the left and right sides. The minimum and maximum velocities for both arms' UWPs were significantly higher in SC1 than in the other three SCs. There were no significant differences in any other pairwise V comparisons, with the exception of the minimum V and the V fluctuation for the left arm UWPs, which decreased from SC2 to SC3.

Table 4.7: Significance levels of the repeated measures ANOVA tests for V maxima/minima and V fluctuations for the right and left sides

	RVMax	**LVMax**	**RVMin**	**LVMin**
Overall	$F_{2.1,21}$=32.1 (p<0.001)*	$F_{3,30}$=28.7 (p<0.001)*	$F_{3,30}$=26.2 (p<0.001)*	$F_{3,30}$=31.1 (p<0.001)*
SC1 / SC2	<0.001*	0.002*	0.001*	0.001*
SC1 / SC3	0.002*	0.001*	<0.001*	<0.001*
SC1 / SC4	<0.001*	<0.001*	<0.001*	0.001*
SC2 / SC3	1.000	0.187	1.000	0.015*
SC2 / SC4	0.312	0.071	0.256	0.110
SC3 / SC4	0.554	1.000	0.975	1.000
	RF	**LF**	**% RF**	**% LF**
Overall	$F_{3,30}$=1.2 (p=0.339)	$F_{1.7,17}$=1.6 (p=0.230)	$F_{3,30}$=0.8 (p=0.528)	$F_{3,30}$=3.4 (p=0.030)*
SC1 / SC2	0.638	1.000	1.000	1.000
SC1 / SC3	1.000	1.000	1.000	0.167
SC1 / SC4	1.000	1.000	1.000	1.000
SC2 / SC3	1.000	0.022*	1.000	0.013*
SC2 / SC4	1.000	1.000	1.000	1.000
SC3 / SC4	1.000	0.078	1.000	0.125

RVMax / RVMin: Maximum / minimum V during right arm UWP
LVMax / LVMin: Maximum / minimum V during left arm UWP
RF / LF: V fluctuation during right / left arm UWP
*: significant at p<.05

4.3.1.3.3 Bilateral asymmetries

- **Asymmetries in minimum and maximum velocity and velocity fluctuation**

Table 4.8 shows the bilateral asymmetries in V maxima/minima and V fluctuations. There were no significant changes throughout the test for the magnitude of bilateral asymmetries in minimum/maximum V ($0.072 \leq p \leq 1.000$) and V fluctuation ($0.423 \leq p \leq 1.000$).

Table 4.8: Bilateral asymmetries in V maxima/minima and V fluctuations

Bilateral Asymmetries	SC1	SC2	SC3	SC4	Mean
Max V	0.15	0.10	0.13	0.11	0.12
($m \cdot sec^{-1}$)	(±0.11)	(±0.06)	(±0.10)	(±0.07)	(±0.07)
Max V – R side bias	0.14	0.09	0.13	0.11	0.12
($m \cdot sec^{-1}$)	(±0.13)	(±0.07)	(±0.10)	(±0.07)	(±0.08)
Min V	0.14	0.09	0.15	0.08	0.11
($m \cdot sec^{-1}$)	(±0.12)	(±0.10)	(±0.11)	(±0.06)	(±0.09)
Min V – R side bias	0.07	0.06	0.13	0.08	0.08
($m \cdot sec^{-1}$)	(±0.17)	(±0.12)	(±0.14)	(±0.09)	(±0.12)
V Fluctuation	0.17	0.12	0.12	0.11	0.12
($m \cdot sec^{-1}$)	(±0.13)	(±0.07)	(±0.10)	(±0.10)	(±0.09)
V Fluctuation – R side bias	0.07	0.04	0.00	0.06	0.04
($m \cdot sec^{-1}$)	(±0.21)	(±0.14)	(±0.16)	(±0.14)	(±0.15)
% V Fluctuation	10.57	8.07	8.33	7.71	7.77
(% of Average V)	(±8.00)	(±4.77)	(±6.89)	(±6.77)	(±6.00)
% V Fluctuation – R side bias	4.23	2.58	0.02	4.18	2.80
(% of Average V)	(±12.92)	(±9.34)	(±11.13)	(±9.59)	(±9.68)

Right (R) side biases were calculated by subtracting the left from the right side values and taking the mean. Asymmetries were then calculated by taking the absolute values for these subtractions and estimating their mean.

The maximum V for the right arm UWP was 0.12 ± 0.08 $m \cdot sec^{-1}$ and the minimum 0.08 ± 0.12 $m \cdot sec^{-1}$ higher than the respective velocities for the left arm UWP. With regard to maximum V, all swimmers displayed consistently the above pattern, with the exception of swimmer 4 who had overall symmetry. However the trend was slightly different for minimum V. Although the group mean of the 200 m V was higher for the right arm UWP, three swimmers had overall symmetry and another two swimmers had higher minimum velocities during the left arm UWP. Maximum V was significantly higher for the right than the left arm UWP in all SCs ($0.001 \leq p \leq 0.005$). Nevertheless, minimum V was significantly higher for the right than the left arm UWP only in SC3 ($p=0.017$).

There were no significant differences in V fluctuations between the left and right arm UWPs for any SCs ($0.320 \leq p \leq 0.971$), with the between swimmers values showing no consistent side bias. The individual data showed that seven swimmers maintained the dominant side (side displaying more fluctuation) throughout the 200 m test, while the remaining four swimmers maintained the dominant side for three of the four SCs.

- **Correlations between variables**

Table 4.9 shows the correlations between average V and the magnitude of asymmetries in V fluctuation and V maxima/minima. There were no significant correlations for any pairs of variables.

Table 4.9: Correlations for CM average V and asymmetries in V fluctuation and V maxima/minima

Variables	SC1	SC2	SC3	SC4	Mean
Average V – Maximum V asymmetries	-0.36 (0.277)	-0.19 (0.576)	-0.22 (0.516)	-0.04 (0.907)	-0.34 (0.306)
Average V – Minimum V asymmetries	-0.07 (0.838)	0.08 (0.815)	-0.18 (0.596)	0.20 (0.555)	0.01 (0.977)
Average V –V fluctuation asymmetries	-0.29 (0.387)	-0.16 (0.638)	-0.29 (0.387)	0.02 (0.954)	-0.16 (0.638)
Average V – % V fluctuation asymmetries	-0.10 (0.770)	0.16 (0.638)	-0.38 (0.249)	0.59 (0.056)	-0.21 (0.535)

p values are shown in the parentheses

Table 4.10 shows the coefficients for correlations between the left and right sides for the V maxima/minima and V fluctuations. There were positive and significant correlations in the V maxima throughout the 200 m. However, minimum velocities of the left and right arm UWPs were significantly correlated only in SC4.

There were no significant correlations between the right and left side values for absolute and percentage V fluctuations. Moreover, the correlation between maximum and minimum V for the same side showed no significant relationships for either side ($0.15 \leq r \leq 0.53$, $0.094 \leq p \leq 0.660$).

Table 4.10: Correlations between left and right sides for V maxima/minima and V fluctuations

Variables	SC1	SC2	SC3	SC4	Mean
Maximum V	0.62	0.87	0.80	0.74	0.81
	(0.042)*	(<0.001)*	(0.003)*	(0.009)*	(0.003)*
Minimum V	-0.19	0.15	0.04	0.61	0.04
	(0.576)	(0.681)	(0.930)	(0.046)*	(0.930)
V Fluctuation	0.08	0.56	0.36	0.14	0.31
	(0.815)	(0.073)	(0.277)	(0.681)	(0.354)
% V Fluctuation	-0.01	0.50	0.20	0.24	0.23
	(0.977)	(0.117)	(0.555)	(0.477)	(0.496)

p values are shown in the parentheses
*: significant at p<.05

4.3.1.4 Timing of velocity maxima and minima

The timings for the two distinct maxima and minima were defined as Max1, Max2, Min1 and Min2, with the order of appearance in the SC used as a criterion. The side of appearance of V maxima/minima was not used as a criterion for the above definitions, due to between swimmer differences in SC start/end side (i.e. the analysed cycles were defined as left-to-left hand entry for some swimmers and right-to-right hand entry for others, due to calibrated volume restrictions).

Figure 4.7 shows the mean values for the timings of maxima/minima for each SC (numerical data are shown in Table C.8, Appendix C). Max1 occurred significantly earlier in SC1 than SC2 ($p=0.011$), SC3 ($p=0.004$) and SC4 ($p=0.009$). Min2 occurred significantly earlier in SC1 than SC3 ($p=0.023$) and SC4 ($p=0.047$). There were no significant differences in the timings of Min1 and Max2 throughout the 200 m ($0.108 \leq p \leq 1.000$). The differences in timings of maxima/minima between SC1 and SC4 varied from 3.0 % to 8.7 %. The timings for both V maxima/minima were not correlated with average V for any SCs ($-0.25 \leq r \leq 0.58$, $0.061 \leq p \leq 0.458$).

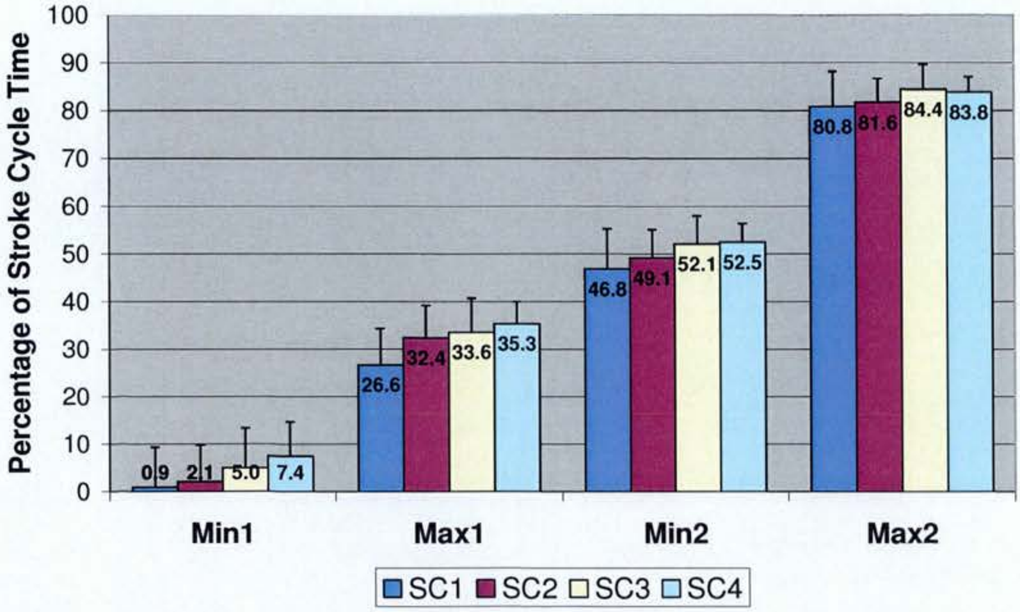

Figure 4.7: Timings of the intracycle horizontal V maxima and minima

4.3.2 Vertical and lateral velocity

4.3.2.1 Velocity patterns

The average V for both lateral and vertical directions was approximately zero as expected (due to swimmers swimming in the middle of a lane, on the water surface), so an analysis of average velocities for these directions would be meaningless.

Noticeable intracycle variations were recorded for the V of the CM in both the lateral and vertical directions. There were no distinct between swimmer patterns in either direction. Nevertheless, individual swimmers were consistent in both the lateral and vertical V patterns across the four SCs. Figures 4.8 to 4.11 show the vertical and lateral V patterns of the CM for different swimmers across the four SCs.

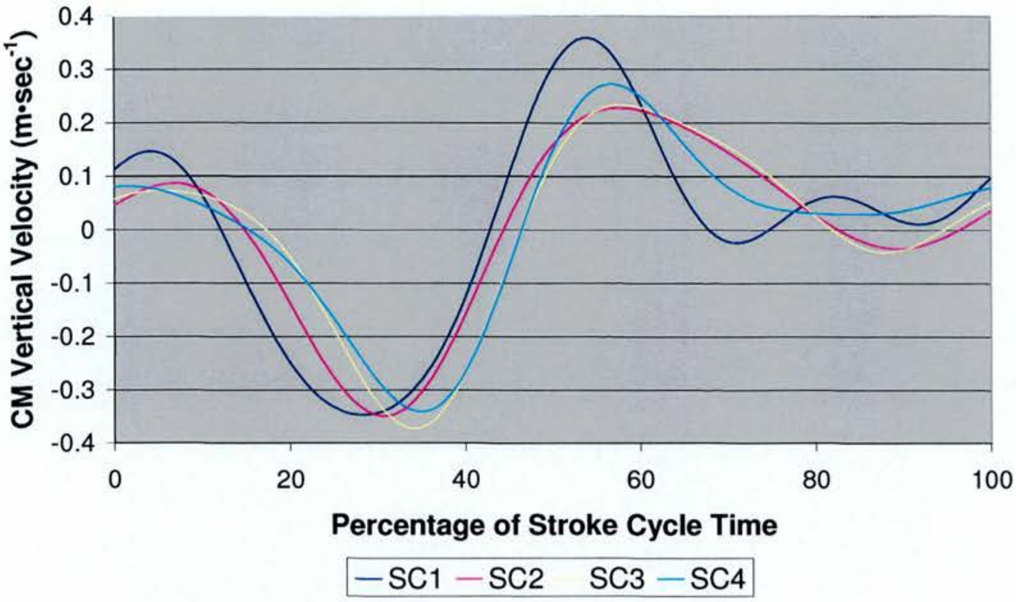

Figure 4.8: Pattern of vertical V of the CM for swimmer 2

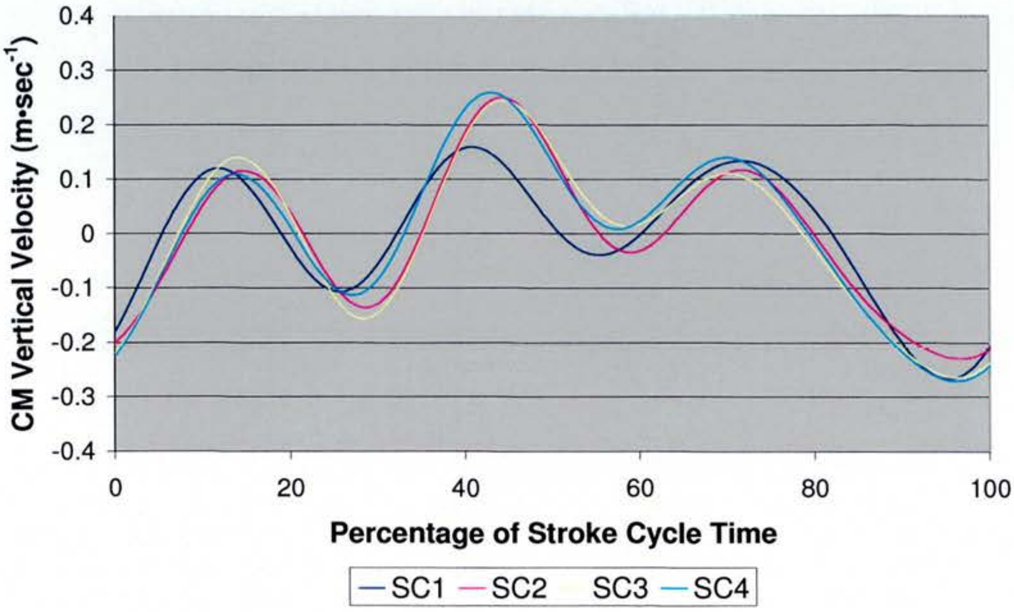

Figure 4.9: Pattern of vertical V of the CM for swimmer 5

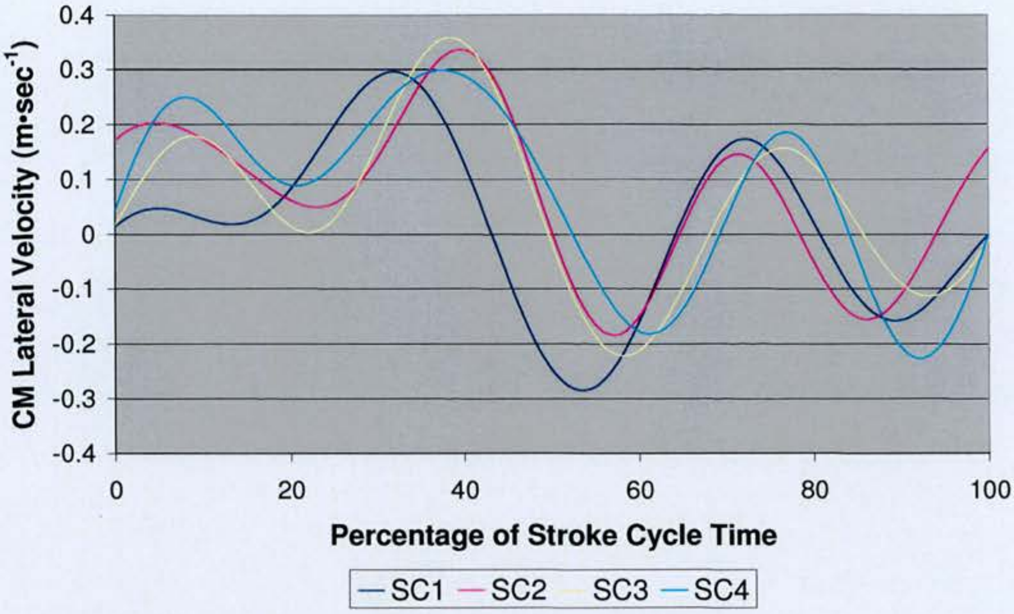

Figure 4.10: Pattern of lateral V of the CM for swimmer 2

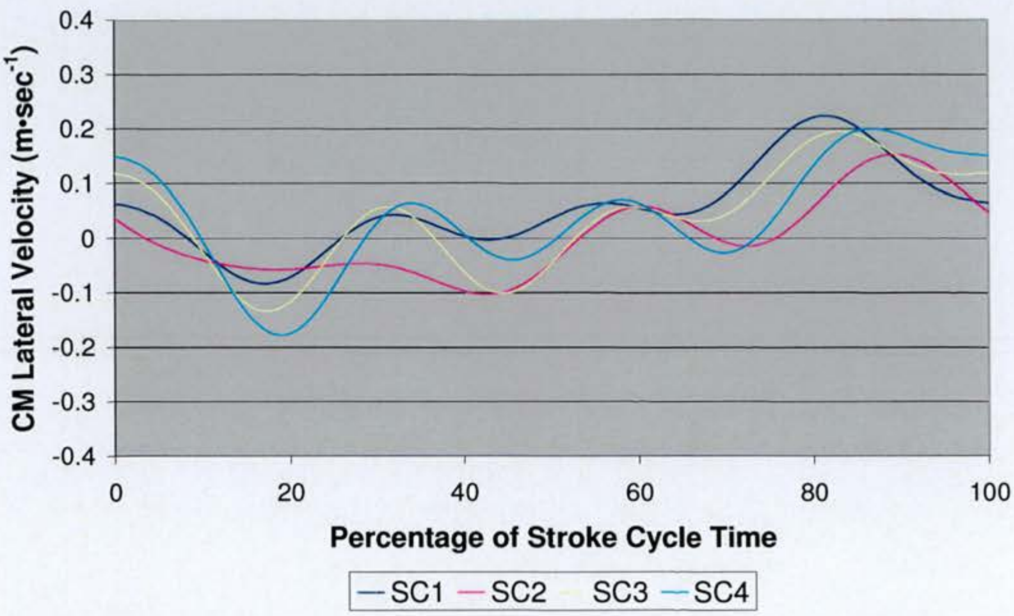

Figure 4.11: Pattern of lateral V of the CM for swimmer 4

4.3.2.2 Velocity fluctuations

Table 4.11 shows the absolute and percentage fluctuations in intracycle vertical and lateral V of the CM for each SC. Swimmers appeared to have higher V fluctuations for the vertical than the lateral direction, with fluctuations in both directions being lower than those in the horizontal direction.

Table 4.11: Fluctuations of the V of the CM in the vertical and lateral directions

Direction of V Fluctuations	Fluctuation ($m \cdot sec^{-1}$)				
	SC1	**SC2**	**SC3**	**SC4**	**Mean**
Vertical	0.59 (±0.11)	0.53 (±0.09)	0.51 (±0.10)	0.51 (±0.08)	0.54 (±0.09)
Lateral	0.43 (±0.10)	0.40 (±0.07)	0.39 (±0.11)	0.38 (±0.10)	0.40 (±0.07)
	% Fluctuation (% of Average Horizontal V)				
	SC1	**SC2**	**SC3**	**SC4**	**Mean**
Vertical	35.57 (±5.85)	35.29 (±5.92)	35.03 (±6.40)	35.58 (±5.82)	35.37 (±5.16)
Lateral	25.73 (±5.99)	26.42 (±4.27)	26.67 (±6.42)	26.19 (±6.35)	26.25 (±4.30)

Table 4.12 shows the significance levels obtained from the repeated measures ANOVA performed for V fluctuations in the vertical and lateral directions. There were no significant differences in the mean absolute and percentage values for any pairs of SCs in both the lateral and vertical directions. Nevertheless, the individual swimmer data showed changes of varying magnitude among swimmers (Tables C.9 and C.10, Appendix C).

Lateral fluctuations were significantly correlated with average V in SC3 ($r=0.81$, $p=0.003$ for the absolute and; $r=0.71$, $p=0.014$ for the percentage fluctuation). There were no other significant correlations between vertical/lateral fluctuations and horizontal V of the CM ($0.01 \leq r \leq 0.57$, $0.067 \leq p \leq 0.977$).

Table 4.13 shows the correlations between all pairs of V fluctuations in all directions. There were positive significant correlations for the mean 200 m fluctuations in most pairs of directions, as well as for some pairwise comparisons for a few SCs.

Table 4.12: Significance levels of the repeated measures ANOVA tests for V fluctuations of the CM in the vertical and lateral directions

	V Fluctuations			
	Vertical		Lateral	
	Absolute	%	Absolute	%
Overall	$F_{3,30}$=6.5 (p=0.002)*	$F_{3,30}$=0.1 (p=0.980)	$F_{3,30}$=0.9 (p=0.449)	$F_{3,30}$=0.1 (p=0.967)
SC1 / SC2	0.093	1.000	1.000	1.000
SC1 / SC3	0.077	1.000	1.000	1.000
SC1 / SC4	0.075	1.000	0.569	1.000
SC2 / SC3	1.000	1.000	1.000	1.000
SC2 / SC4	1.000	1.000	1.000	1.000
SC3 / SC4	1.000	1.000	1.000	1.000

*: significant at p<.05

Table 4.13: Correlations between V fluctuations of the CM in the three directions

	Fluctuation Correlations				
	SC1	**SC2**	**SC3**	**SC4**	**Mean**
HF/VF	0.54(0.086)	0.48(0.135)	0.31(0.354)	0.43(0.187)	0.60(0.050)*
HF/LF	0.69(0.019)*	0.66(0.027)*	0.44(0.176)	-0.09(0.792)	0.67(0.024)*
VF/LF	0.37(0.263)	0.13(0.703)	0.67(0.024)*	0.37(0.263)	0.71(0.014)*
	% Fluctuation Correlations				
	SC1	**SC2**	**SC3**	**SC4**	**Mean**
HF/VF	0.49(0.126)	0.39(0.236)	0.17(0.617)	0.44(0.176)	0.49(0.126)
HF/LF	0.68(0.021)*	0.57(0.067)	0.23(0.496)	-0.19(0.576)	0.60(0.050)*
VF/LF	0.32(0.337)	-0.05(0.884)	0.55(0.080)	0.26(0.440)	0.64(0.034)*

HF / VF / LF: Horizontal / Vertical / Lateral fluctuation of CM
p values are shown in the parentheses
*: significant at p<.05

4.4 Kinematic parameters of the trunk: shoulder and hip roll

4.4.1 Overall roll changes

Figure 4.12 shows the range of shoulder and hip roll for the group of swimmers throughout the 200 m test. Swimmers rolled their shoulders considerably more than their hips. The mean roll values for the 200 m were 105.5 ± 0.9° and 50.0 ± 5.0° for the shoulders and hips, respectively. Individual data are shown in Table C.11 (Appendix C).

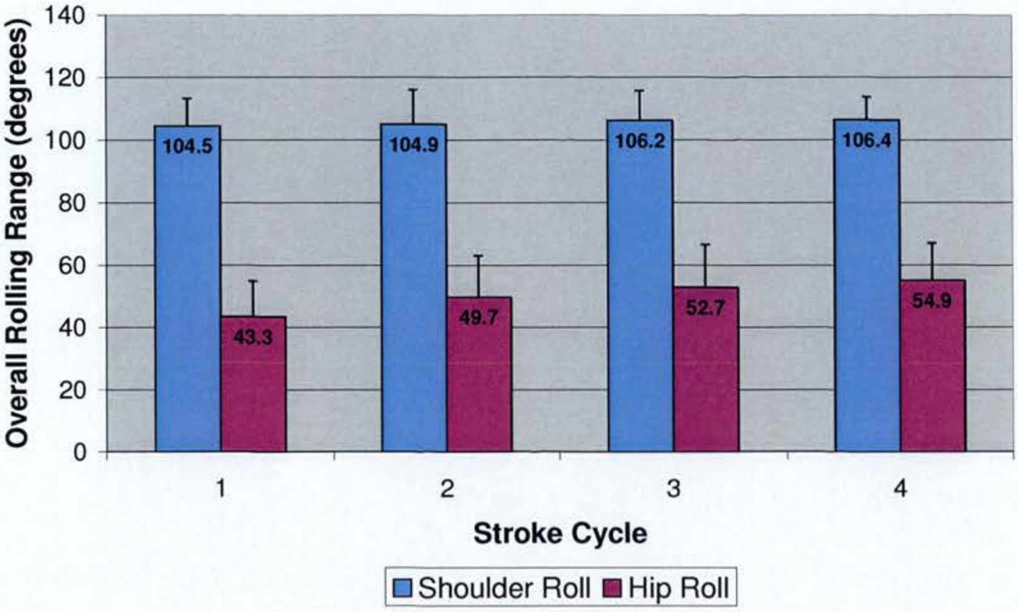

Figure 4.12: Range of overall shoulder and hip roll

Table 4.14 shows the significance levels of the repeated measures ANOVA tests for shoulder and hip roll. There were no significant changes in shoulder roll between any pairs of SCs. The mean shoulder roll values increased by 1.9° from SC1 to SC4, which falls within the reliability limits shown in Table 4.1 (section 4.1). However, the mean increases in hip roll from SC1 to SC4 (11.6°) were greater than that of shoulder roll. Hip roll was significantly lower in SC1 than the other three SCs.

Table 4.15 shows the correlation between average V and shoulder/hip roll, as well as between shoulder roll and hip roll. The correlations between shoulder/hip roll and average V were negative and not significant. Ranges of shoulder and hip roll were positively correlated in all SCs, but the correlations were significant only in SC2 and SC4.

Table 4.14: Significance levels of the repeated measures ANOVA tests for shoulder and hip roll

	Shoulder Roll	Hip Roll
Overall	$F_{3,30}$=0.4 (p=0.731)	$F_{1.7,17}$=8.5 (p=0.004)*
SC1 / SC2	1.000	0.004*
SC1 / SC3	1.000	0.046*
SC1 / SC4	1.000	<0.001*
SC2 / SC3	1.000	1.000
SC2 / SC4	1.000	0.305
SC3 / SC4	1.000	1.000

*: significant at p<.05

Table 4.15: Correlations between shoulder/hip roll and CM average V

	SC1	SC2	SC3	SC4	Mean
Shoulder Roll / Average V	-0.29 (0.387)	-0.21 (0.535)	-0.50 (0.117)	-0.38 (0.249)	-0.40 (0.223)
Hip Roll / Average V	-0.31 (0.354)	-0.17 (0.638)	-0.57 (0.067)	-0.48 (0.135)	-0.40 (0.223)
Shoulder Roll / Hip Roll	0.33 (0.322)	0.62 (0.042)*	0.48 (0.135)	0.60 (0.050)*	0.57 (0.67)

p values are shown in the parentheses
*: significant at p<.05

4.4.2 Roll patterns

Shoulder and hip roll patterns were sinusoidal in appearance for all swimmers throughout the test. There were two distinct maximum roll values for both shoulders and hips, corresponding to maximum roll on the left and right sides. The results showed asymmetries in the magnitude of shoulder and hip roll for the left and right sides. These asymmetries are presented in section 4.4.3. Moreover, the analysis of the timings of shoulder and hip roll maxima (presented in section 4.4.4) showed non-significant differences. The latter, together with intracycle analysis of roll, indicated that swimmers were generally rolling the shoulders and hips towards the same direction during the SC. Figures 4.13 and 4.14 illustrate the rolling patterns of two swimmers that displayed symmetrical (Figure 4.13) and non-symmetrical (Figure 4.14) magnitude of roll between the left and right sides for both shoulders and hips.

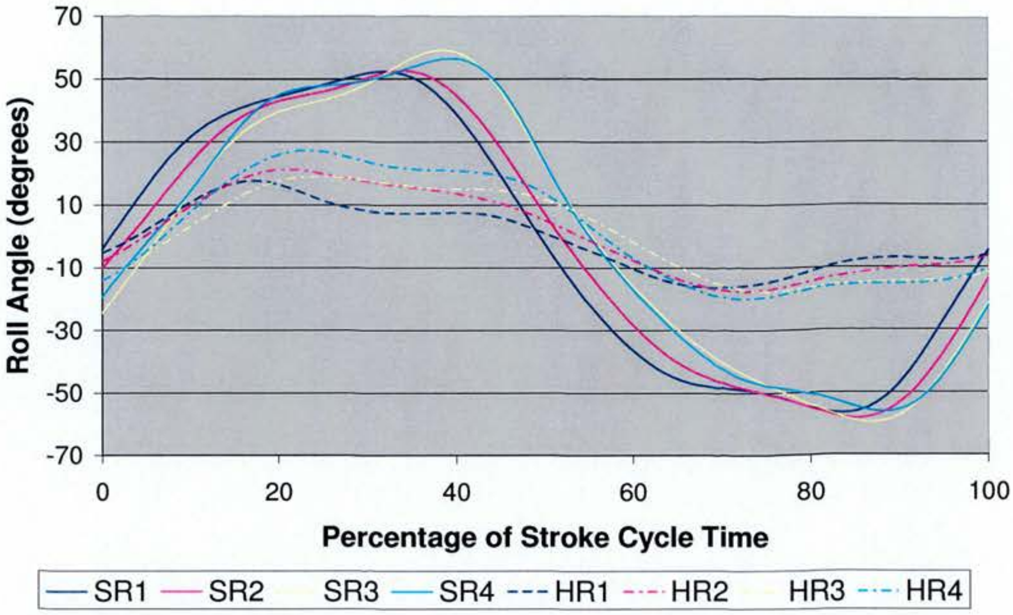

Figure 4.13: Patterns of shoulder (SR) and hip (HR) roll for swimmer 7

Positive/negative roll values represent roll to the right/left side, respectively
Shoulder/hip roll patterns were symmetrical with regard to roll magnitude on each side

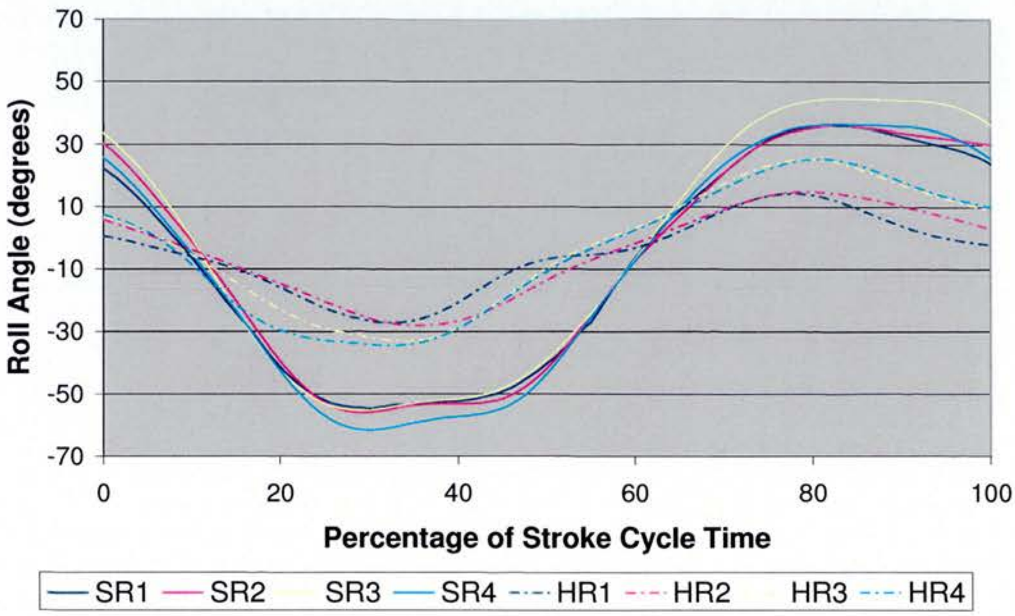

Figure 4.14: Patterns of shoulder (SR) and hip (HR) roll for swimmer 4

Positive/negative roll values represent roll to the right/left side, respectively
Shoulder/hip roll patterns were non-symmetrical with regard to roll magnitude on each side

4.4.3 Analysis of roll for the left and right sides

4.4.3.1 Changes throughout the test

Figure 4.15 shows the mean shoulder/hip roll values for the left and right sides throughout the 200 m test. Individual swimmer data are shown in Tables C.12 and C.13 (Appendix C).

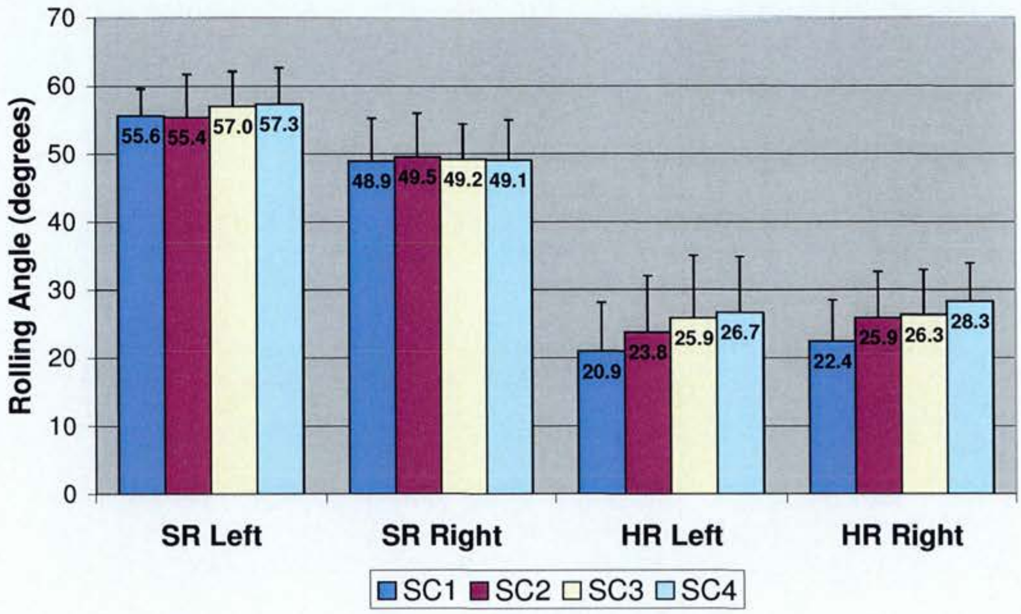

Figure 4.15: Range of shoulder and hip roll to the left (SR Left, HR Left) and right (SR Right, HR Right) sides

Table 4.16 shows the significance levels obtained from the repeated measures ANOVA for the right and left side values for shoulder/hip roll. Similar to the trends in the overall roll values (section 4.4.1), mean group values showed only minor changes (up to 1.9°) in shoulder roll between any two SCs for each side, which fall within the reliability limits shown in Table 4.1 (section 4.1). There were larger changes in hip roll (up to 5.9°) than shoulder roll for pairs of SCs in both sides. Hip roll for both sides was significantly less in SC1 than SC2 and SC4. The lack of significance between SC1 and SC3 was probably due to larger variability in individual swimmer values. The changes in shoulder/hip roll were not significant for any other pairs of SCs.

Table 4.16: Significance levels of the repeated measures ANOVA tests for shoulder and hip roll for the left and right sides

	Roll			
	Left side		Right side	
	Shoulder	Hip	Shoulder	Hip
Overall	$F_{3,30}$=1.0 (p=0.429)	$F_{3,30}$=5.7 (p=0.003)*	$F_{3,30}$=0.8 (p=0.973)	$F_{3,30}$=6.1 (p=0.002)*
SC1 / SC2	1.000	0.039*	1.000	0.013*
SC1 / SC3	1.000	0.167	1.000	0.108
SC1 / SC4	1.000	0.002*	1.000	0.002*
SC2 / SC3	1.000	1.000	1.000	1.000
SC2 / SC4	1.000	0.348	1.000	0.760
SC3 / SC4	1.000	1.000	1.000	1.000

*: significant at p<.05

4.4.3.2 Bilateral asymmetries

- **Asymmetries in shoulder and hip roll**

Table 4.17 summarises the bilateral asymmetries in shoulder/hip roll throughout the test. There were no significant changes throughout the test in the magnitude of bilateral asymmetries in shoulder ($0.667 \le p \le 1.000$) and hip roll (p=1.000). All swimmers (with the exception of swimmer 2, who showed overall symmetry) had overall left side dominance in shoulder roll. Shoulder roll values were significantly higher on the left than the right side for all SCs and the mean 200 m values ($0.001 \le p \le 0.013$). On the contrary, there were no significant differences between hip roll on the left and the right sides ($0.374 \le p \le 0.828$). There was no common trend with regard to the side having larger hip roll values, with four swimmers displaying overall symmetry, another four having left side dominance and the remaining three showing right side dominance. Finally, all swimmers with lateral dominance in shoulder and/or hip roll were consistent throughout the 200 m with respect to the side that had larger roll.

Table 4.17: Bilateral asymmetries in shoulder and hip roll

Roll Asymmetries (degrees)	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**
Shoulder	6.8	6.9	7.8	9.6	7.8
	(±5.7)	(±5.2)	(±3.9)	(±6.8)	(±4.6)
Shoulder – Left side bias	6.7	5.9	7.8	8.2	7.2
	(±5.9)	(±6.4)	(±3.9)	(±8.6)	(±5.1)
Hip	5.1	6.2	5.4	5.7	5.6
	(±4.8)	(±4.3)	(±3.8)	(±4.9)	(±3.8)
Hip – Left side bias	-1.5	-2.1	-0.5	-1.6	-1.4
	(±7.0)	(±7.5)	(±6.8)	(±7.5)	(±6.6)

Left side biases were calculated by subtracting the right from the left side values and taking the mean. Asymmetries were calculated by taking the absolute values for these subtractions and estimating their mean.

- **Correlations between variables**

Table 4.18 shows the correlation coefficients between CM average V and the following: shoulder/hip roll in the right and left sides, shoulder/hip roll asymmetries. The correlations between right and left side values for roll and average horizontal V were not significant (with the exception of two values). There was no significant correlation between average V and the magnitude of asymmetries in roll.

Table 4.19 shows the correlations between shoulder and hip roll for the left and right sides. Shoulder/hip roll at the left side were significantly correlated with shoulder/hip roll at the right side only in SC3. For the left side, there was a positive and significant correlation between shoulder and hip roll for SC2, SC4 and the mean 200 m values.

Table 4.18: Correlations between CM average V and the following variables: shoulder/hip roll in the right and left sides, shoulder/hip roll asymmetries

	SC1	SC2	SC3	SC4	Mean
Shoulder Roll Left	-0.05 (0.884)	-0.19 (0.576)	-0.50 (0.117)	-0.28 (0.404)	-0.40 (0.223)
Hip Roll Left	-0.17 (0.617)	-0.15 (0.660)	-0.47 (0.145)	-0.19 (0.576)	-0.26 (0.440)
Shoulder Roll Right	-0.37 (0.263)	-0.18 (0.596)	-0.44 (0.176)	-0.22 (0.516)	-0.30 (0.370)
Hip Roll Right	-0.39 (0.236)	-0.14 (0.681)	-0.60 (0.050)*	-0.72 (0.013)*	-0.47 (0.145)
Shoulder Roll Asymmetries	0.39 (0.236)	0.01 (0.977)	-0.07 (0.838)	-0.05 (0.884)	0.03 (0.930)
Hip Roll Asymmetries	0.22 (0.516)	-0.03 (0.930)	-0.34 (0.306)	-0.26 (0.440)	-0.06 (0.861)

p values are shown in the parentheses
*: significant at p<.05

Table 4.19: Correlations between shoulder and hip roll for the left and right sides

	SC1	SC2	SC3	SC4	Mean
Shoulder Roll Left / Shoulder Roll Right	0.43 (0.187)	0.50 (0.117)	0.72 (0.113)*	0.28 (0.404)	0.47 (0.145)
Hip Roll Left / Hip Roll Right	0.47 (0.145)	0.53 (0.094)	0.68 (0.021)*	0.46 (0.155)	0.54 (0.086)
Shoulder Roll Left / Hip Roll Left	0.31 (0.354)	0.64 (0.034)*	0.53 (0.094)	0.77 (0.006)*	0.67 (0.024)*
Shoulder Roll Right / Hip Roll Right	0.46 (0.155)	0.61 (0.046)*	0.27 (0.422)	0.34 (0.306)	0.46 (0.155)

p values are shown in the parentheses
*: significant at p<.05

4.4.4 Timing of roll maxima

As described in section 4.4.2, both shoulder and hip roll had a single maximum, on each side. With the order of appearance in the SC as a criterion, these maxima were defined as SR-Max1, SR-Max2, HR-Max1 and HR-Max2. Figure 4.16

shows the timings for all maxima throughout the 200 m test. Individual swimmer data are shown in Tables C.14 and C.15 (Appendix C).

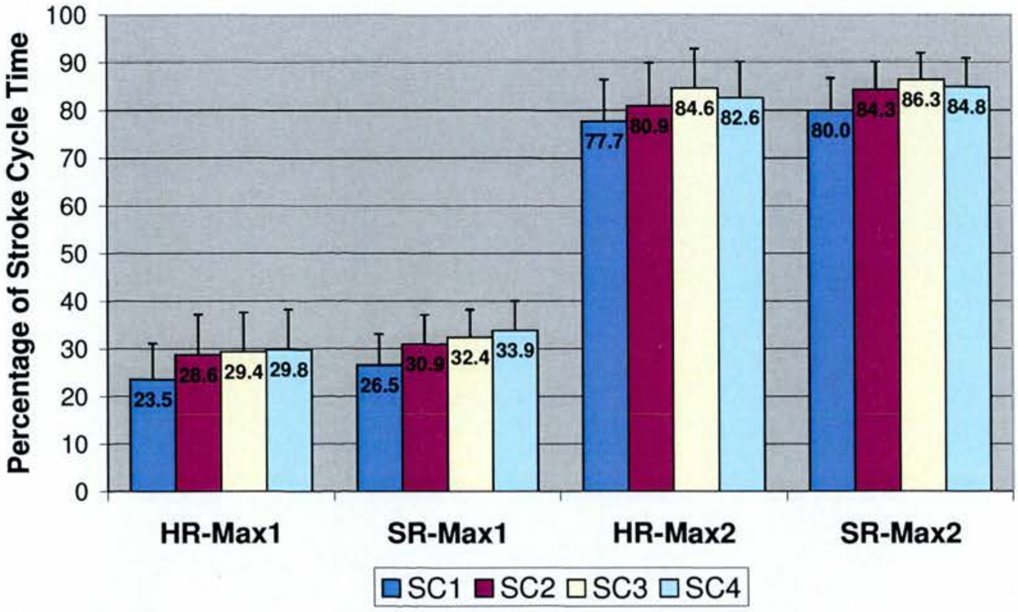

Figure 4.16: Timings of the two shoulder (SR-Max1 and SR-Max2) and hip roll (HR-Max1 and HR-Max2) maxima

Table 4.20 shows the significance levels of the repeated measures ANOVA tests for the timings of shoulder and hip roll for the left and right sides. All maxima occurred significantly earlier in SC1 than SC2, SC3 and SC4 (with the exception of HR-Max2 in SC2). There were no significant differences in the timings of any roll maxima between SC2, SC3 and SC4. Swimmers had some differences between the timings of SR-Max1 and HR-Max1, as well as the timings of SR-Max2 and HR-Max2. However, these differences were very small (ranging from 1.7 % to 4.1 % of SC time) and not significant for any pairs of maxima in all SCs ($0.2165 \leq p \leq 0.523$). Finally, the timings of shoulder/hip roll were not correlated with average swimming V ($-0.42 \leq r \leq 0.48$, $0.135 \leq p \leq 0.930$).

Table 4.20: Significance levels of the repeated measures ANOVA tests for the timings of shoulder and hip roll for the left and right sides

	Roll Maxima			
	Shoulder		Hip	
	1	2	1	2
Overall	$F_{3,30}=14.7$ (p<0.001)*	$F_{3,30}=9.4$ (p<0.001)*	$F_{3,30}=11.1$ (p<0.001)*	$F_{3,30}=6.3$ (p=0.002)*
SC1 / SC2	0.030*	0.018*	0.013*	0.185
SC1 / SC3	0.021*	0.025*	0.019*	0.046*
SC1 / SC4	0.001*	0.048*	0.021*	0.040*
SC2 / SC3	1.000	0.922	1.000	0.632
SC2 / SC4	0.082	1.000	1.000	0.469
SC3 / SC4	0.727	0.624	1.000	1.000

*: significant at p<.05

Interestingly, the mean values for shoulder/hip roll maxima and the two horizontal V maxima suggested that swimmers reached maximum horizontal V and maximum shoulder/hip roll at the same part of the SCs. There were no significant differences between the timings for V maxima and shoulder/hip roll maxima ($0.088 \leq p \leq 0.963$). The differences in timing between maximum V and maximum shoulder roll ranged from 0.1 % to 2.6 %, while the differences between maximum V and maximum hip roll ranged from 0.1 % to 5.4 %.

4.5 Kinematic parameters of the upper and lower extremity

4.5.1 Elbow angular motion during the underwater phases

4.5.1.1 Angular patterns

Figure 4.17 illustrates a typical pattern for the angular ROM of the elbow for one of the swimmers tested in this study (discontinued parts in the figure correspond to the above water arm recovery). In general, swimmers' arms displayed the following pattern during the UWP of the stroke: entered the water slightly flexed and glided forward (until the 'catch') to stretch to almost 180°, then started flexing until reaching the MEF and, finally, stretched again until exiting the water. The elbow pattern presented one distinct MEF value (minimum elbow joint angle) for all swimmers throughout the test. MEF in all swimmers occurred during the second half of the UWP of the stroke (elbow behind the shoulder on the horizontal axis), when the hand was moving backwards and upwards.

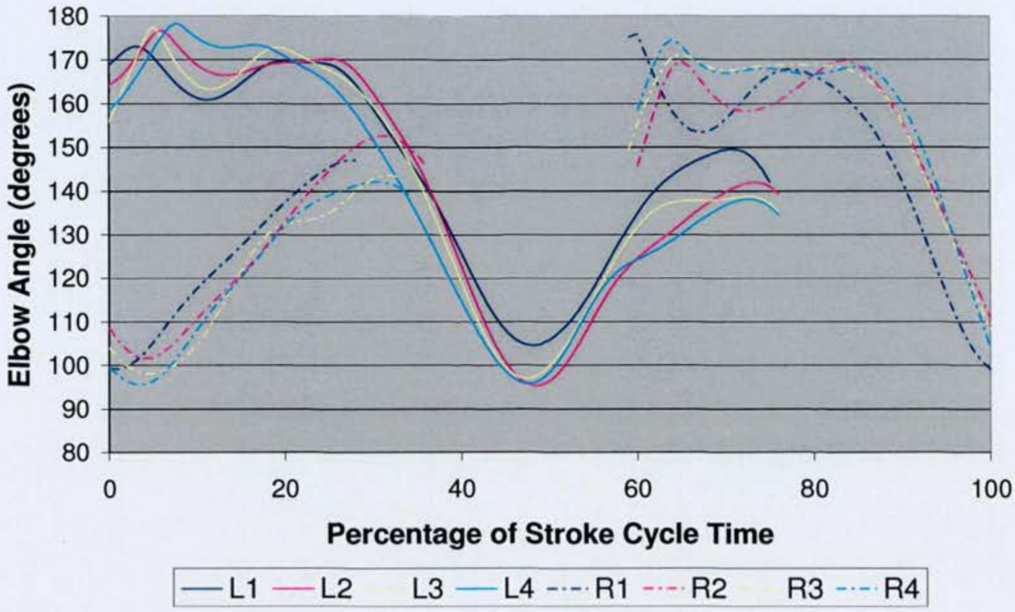

Figure 4.17: Angular motion throughout the four SCs for the left (L1, L2, L3, L4) and the right elbow joints (R1, R2, R3, R4) during the UWP of the stroke for swimmer 5 Discontinued parts correspond to above-water arm recovery.

4.5.1.2 Analysis of maximum flexion for the left and right elbows

4.5.1.2.1 Changes throughout the test

Figure 4.18 shows the mean values for minimum right/left elbow angle (corresponding to MEF) for the whole group throughout the 200 m test (individual swimmer data are shown in Table C.16, Appendix C). Swimmers flexed their left elbows significantly less in SC1 than SC2 ($p=0.046$), SC3 ($p=0.014$) and SC4 ($p=0.011$). The smaller variation in the right MEF values resulted in significant differences only between SC1 and SC4 ($p=0.035$). There were no significant differences for either MEF angle between SC2, SC3 and SC4 ($0.101 \leq p \leq 1.000$).

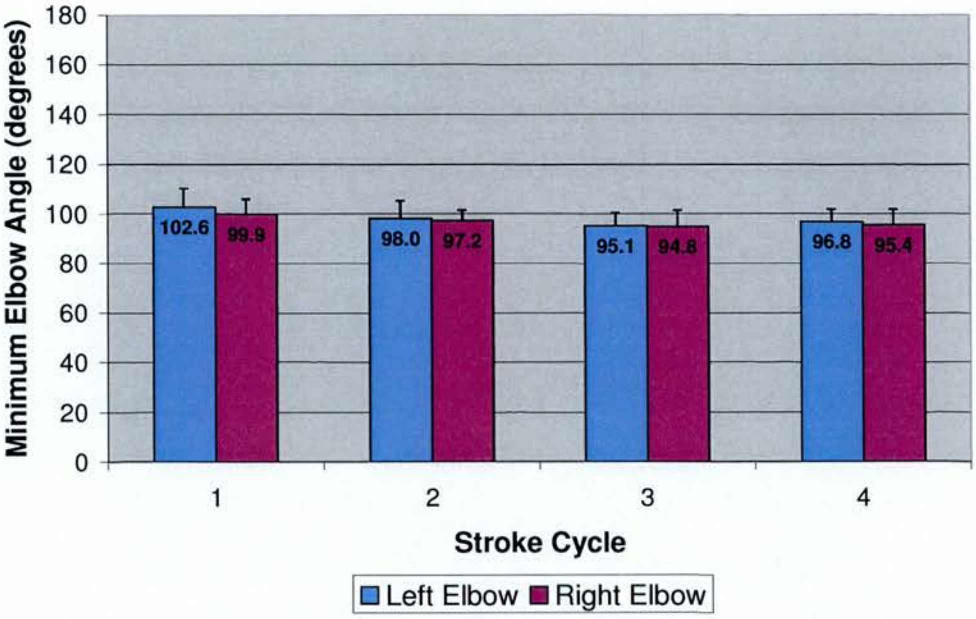

Figure 4.18: Minimum angle (maximum flexion) during the UWP of the stroke for the left and right elbows

4.5.1.2.2 Bilateral asymmetries

- **Bilateral asymmetries in maximum underwater elbow flexion**

Table 4.21 summarises the bilateral asymmetries for MEF during the UWP of the stroke. There were no significant changes throughout the test for the magnitude of bilateral asymmetries in MEF ($0.189 \leq p \leq 1.000$). Moreover, there was no consistent side bias in the side (right or left) for which there was greater MEF. From the eleven swimmers tested, five had more MEF in the right elbow and two in the left elbow, with the remaining four showing overall symmetry (mean difference less than the calculated reliability values). The differences between left and right MEF were not significant for any SCs ($0.074 \leq p \leq 0.896$). Despite the small magnitude of bilateral asymmetries, the within swimmer patterns showed that swimmers who had overall side dominance maintained the side bias in MEF throughout the 200 m (with the exception of swimmer 7).

Table 4.21: Bilateral asymmetries in MEF during the UWP of the stroke

Bilateral Asymmetries (degrees)	SC1	SC2	SC3	SC4	Mean
Maximum Elbow Flexion	4.0 (±3.2)	5.9 (±3.8)	5.4 (±5.2)	4.7 (±3.3)	5.0 (±2.2)
Maximum Elbow Flexion – Right side bias	2.7 (±4.5)	0.8 (±7.2)	0.3 (±7.7)	1.4 (±5.8)	1.3 (±5.1)

Right side biases were calculated by subtracting the right from the left side values and taking the mean. Asymmetries were calculated by taking the absolute values for these subtractions and estimating their mean.

- **Correlations between variables**

Table 4.22 shows correlations between different pairs of the following parameters: right and left side values for MEF, MEF asymmetries and, average V. There were positive correlations between MEF for the left and right sides, but were significant only for SC1 and the mean 200 m values. There were no significant correlations between right/left side values for MEF and average V. Finally, the magnitude of bilateral asymmetry in MEF was not correlated significantly with average CM V.

Table 4.22: Correlations between pairs of the following variables: right and left side values for MEF, MEF asymmetries and, average V

	SC1	SC2	SC3	SC4	Mean
MEF Left / MEF Right	0.81 (0.003)*	0.33 (0.322)	0.21 (0.535)	0.51 (0.109)	0.61 (0.046)*
MEF Left / Average V	0.21 (0.535)	0.20 (0.555)	-0.33 (0.322)	-0.40 (0.223)	-0.07 (0.838)
MEF Right / Average V	0.20 (0.555)	0.05 (0.884)	0.36 (0.277)	-0.55 (0.080)	0.09 (0.792)
MEF Asymmetries / Average V	0.26 (0.440)	0.48 (0.135)	0.40 (0.223)	-0.42 (0.198)	0.55 (0.080)

p values are shown in the parentheses
*: significant at p<.05

4.5.1.3 Timing of maximum elbow flexion

According to order of appearance in the SC, the two timings of MEF (one for each elbow) were defined as MEF1 and MEF2. Figure 4.19 shows these timings throughout the 200 m test. Individual swimmer data are shown in Table C.17 (Appendix C).

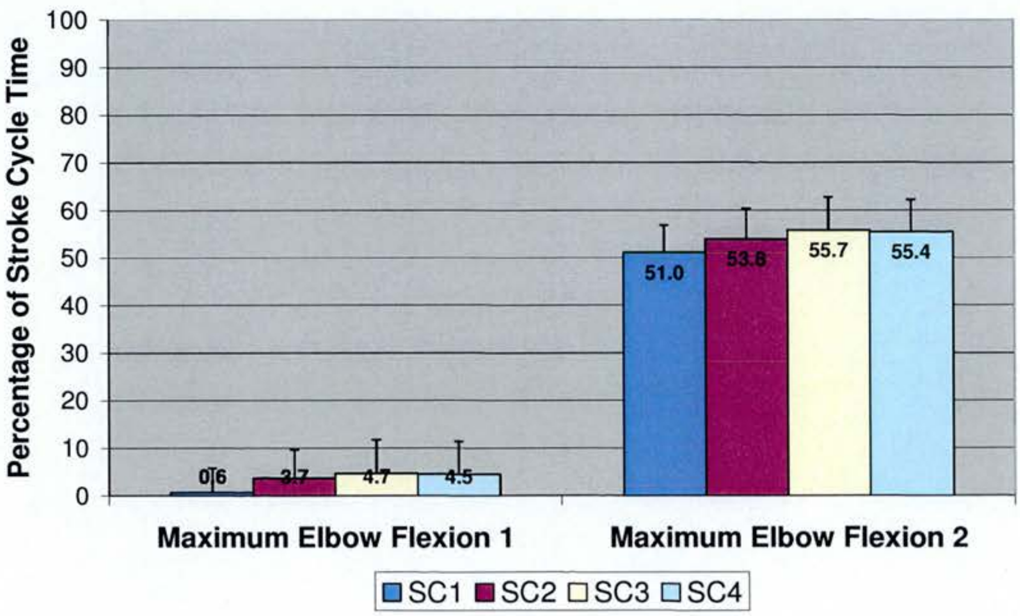

Figure 4.19: Timings of the two maximum flexions of the elbows

There were no significant changes in the timings of either MEF for any pairs of SCs ($0.074 \leq p \leq 1.000$). Average V in SC1 was significantly correlated with the timings of MEF1 ($r = 0.67$, $p=0.024$) and MEF2 ($r = 0.79$, $p=0.004$). However, there were no other significant correlations between average V and timings of MEF for any SCs ($0.07 \leq r \leq 0.46$, $0.155 \leq p \leq 0.838$).

The mean values for the timings of MEF and the two minima for horizontal V of the CM suggested that swimmers had minimum horizontal V and MEF at the same part of the SC. There were no significant differences between the timings for V minima and elbow flexion maxima for any SCs ($0.120 \leq p \leq 0.926$). The differences in timing between minimum V and MEF ranged from 0.3 % to 4.2 %.

4.5.2 Knee angular motion

4.5.2.1 Angular patterns

Most swimmers employed a six-beat kicking pattern for each SC throughout the 200 m. However, the between and within swimmer kicking patterns presented some variations. For example, swimmer 5 had a four-beat kicking pattern while swimmers 10 and 11 started with a six-beat and switched to a two-beat kicking pattern in SC3 and SC4. Figures 4.20 and 4.21 illustrate the left and right knee angular patterns for a swimmer who used a six-beat kicking pattern throughout the test, while Figure 4.22 shows the left knee patterns for a swimmer who switched from a six-beat (in SC1 and SC2) to a two-beat kicking pattern (in SC3 and SC4).

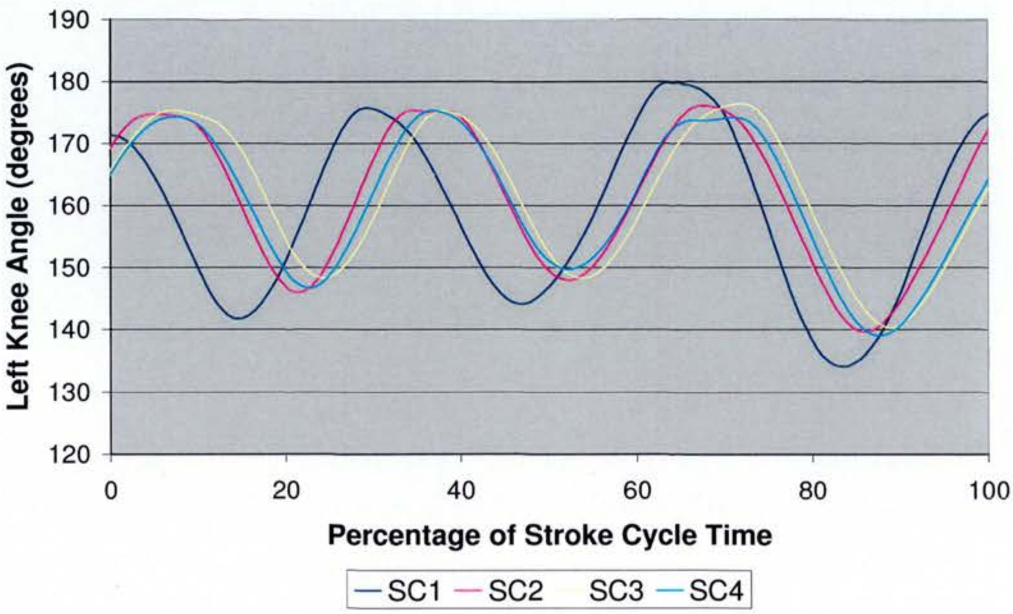

Figure 4.20: Angular motion of the left knee for swimmer 8

This swimmer used a six-beat kicking pattern

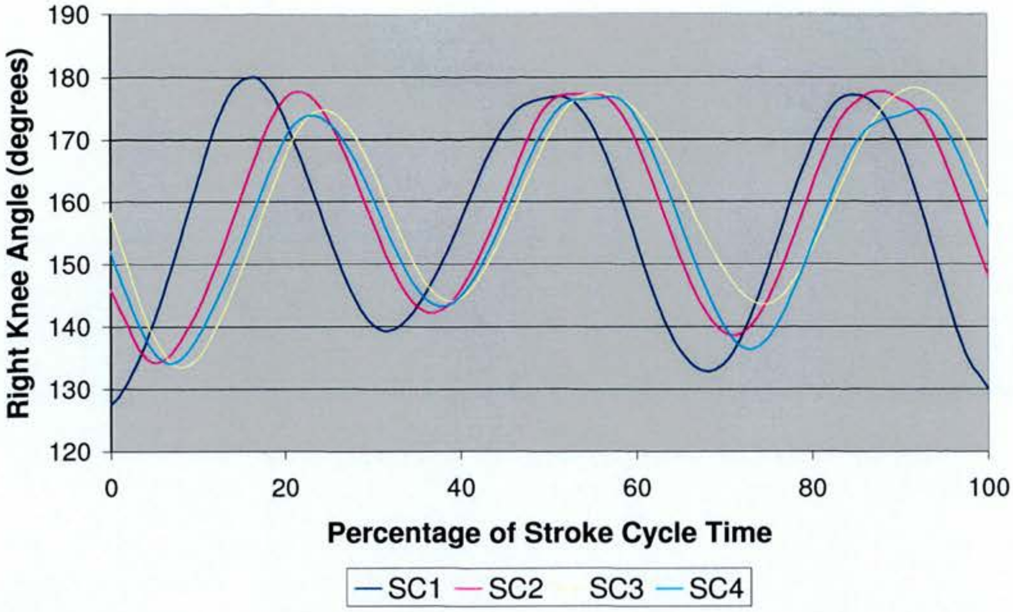

Figure 4.21: Angular motion of the right knee for swimmer 8

This swimmer used a six-beat kicking pattern

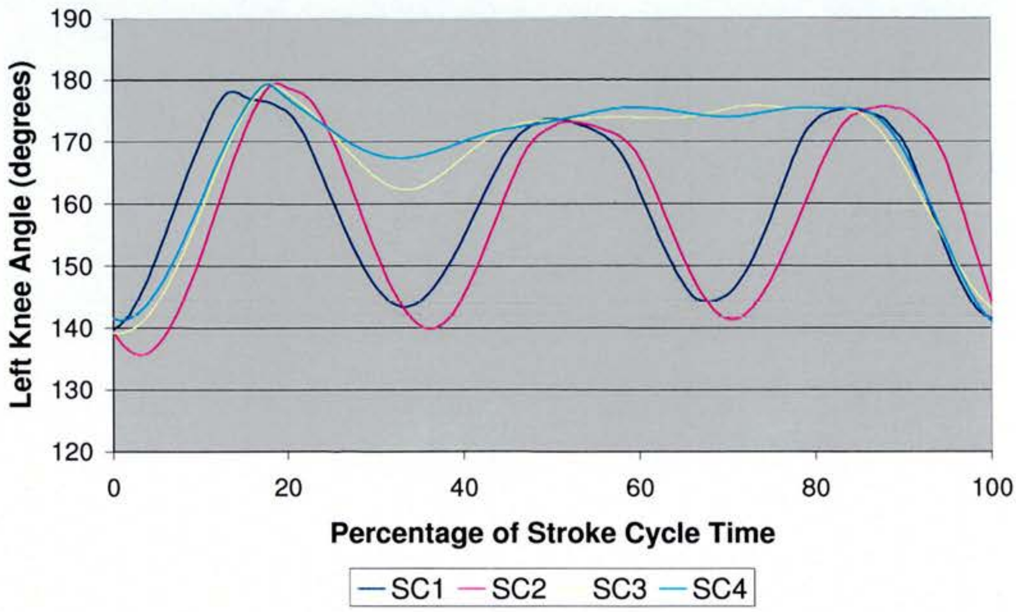

Figure 4.22: Angular motion of the left knee for swimmer 11

This swimmer switched from a six-beat to a two-beat kicking pattern in SC3

4.5.2.2 Analysis of maximum flexion for the left and right knees

4.5.2.2.1 Changes throughout the test

Figure 4.23 shows the minimum angle (representing MKF) for the left and right knees throughout the 200 m test (individual swimmer data are presented in Table C.18, Appendix C). There were no significant changes in maximum flexion between any pairs of SCs for both knees ($0.214 \leq p \leq 1.000$). Swimmers reached MKF values of similar magnitude several times during each SC, depending on the kicking pattern used (e.g. see Figures 4.20 to 4.22, section 4.5.2.1).

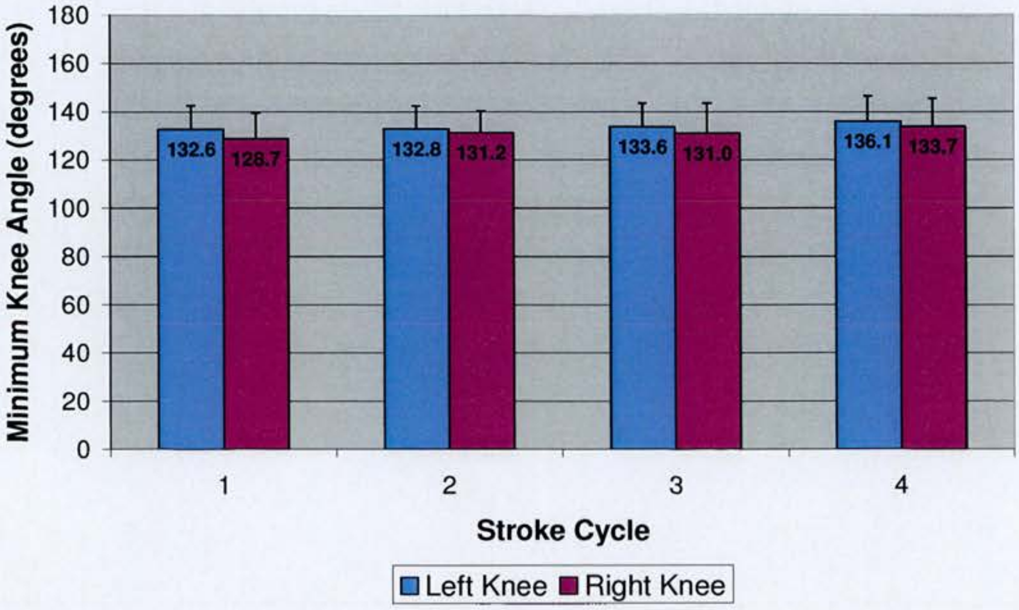

Figure 4.23: Minimum angle (maximum flexion) for the left and right knees

4.5.2.2.2 Bilateral asymmetries

- **Bilateral asymmetries in maximum knee flexion**

Table 4.23 shows the bilateral asymmetries in MKF throughout the test. There were no significant differences in the magnitude of bilateral asymmetries in MKF throughout the test ($p=1.000$). There was high between swimmer variability in the side having more MKF, with six swimmers displaying more MKF for the left and five swimmers more MKF for the right knee. The differences between left and right MKF were not significant for any SCs ($0.245 \leq p \leq 0.668$). Finally, the majority of swimmers (with the exception of swimmers 5 and 11) maintained the side bias in MKF throughout the 200 m.

Table 4.23: Bilateral asymmetries in MKF

Bilateral Asymmetries (degrees)	SC1	SC2	SC3	SC4	Mean
Maximum Knee Flexion	8.5 (±6.5)	9.3 (±7.0)	8.4 (±5.5)	8.1 (±6.3)	8.6 (±5.5)
Maximum Knee Flexion – Right side bias	3.8 (±10.3)	1.6 (±11.9)	2.6 (±10.0)	2.3 (±10.3)	2.6 (±9.9)

Right side biases were calculated by subtracting the right from the left side values and taking the mean. Asymmetries were then calculated by taking the absolute values for these subtractions and estimating their mean.

- **Correlations between variables**

Table 4.24 shows the correlations between pairs of the following parameters: right and left side values for MKF, MKF asymmetries and, average V. The calculated coefficients between the left and right side MKF values were significant only in SC3. There were no significant correlations between average V and right/left side values of MKF. Finally, average V was not correlated significantly with the magnitude of bilateral asymmetry in MKF.

Table 4.24: Correlations between pairs of the following parameters: right and left side values for MKF, MKF asymmetries and, average V

	SC1	SC2	SC3	SC4	Mean
MKF Left / MKF Right	0.50 (0.117)	0.16 (0.638)	0.62 (0.042)*	0.56 (0.073)	0.48 (0.135)
MKF Left / Average V	0.23 (0.496)	0.09 (0.792)	0.30 (0.370)	-0.03 (0.930)	0.19 (0.596)
MKF Right / Average V	0.01 (0.977)	0.10 (0.770)	0.35 (0.291)	-0.08 (0.815)	0.15 (0.660)
MKF Asymmetries / Average V	-0.16 (0.638)	0.17 (0.617)	-0.30 (0.370)	-0.36 (0.277)	-0.27 (0.422)

p values are shown in the parentheses
*: significant at p<.05

4.5.2.3 Timing of maximum knee flexion

As described in section 4.5.2.1, the kicking patterns varied both between and within swimmers. Moreover, there were between and within swimmer differences in the appearance of MKF during a SC. For example, Figure 4.24 shows the right knee kicking pattern of a swimmer who had MKF during the second kick in SC3, rather than in the first kick as in the other three SCs.

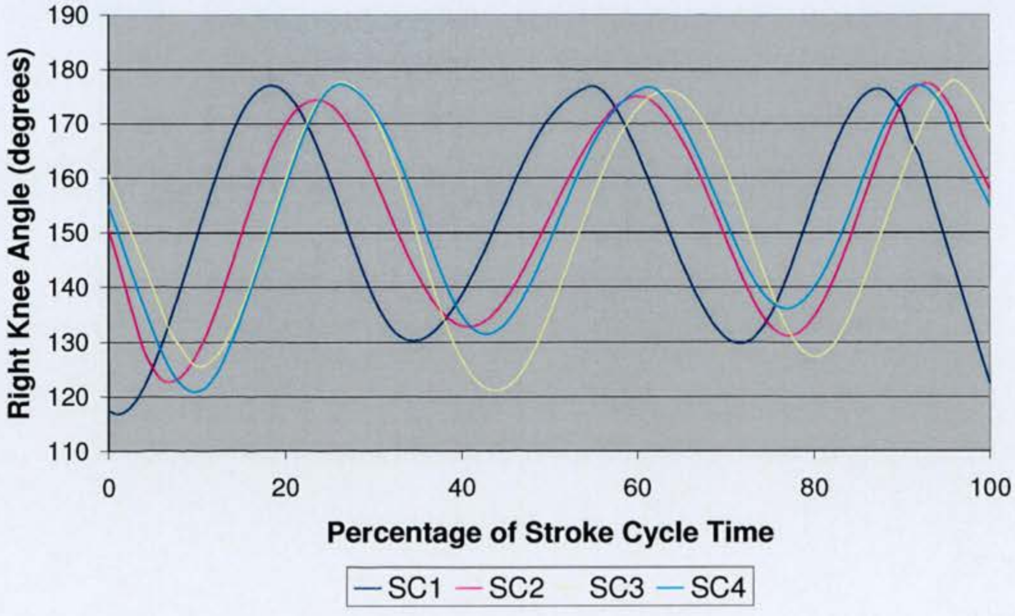

Figure 4.24: Angular motion of the right knee for swimmer 9

This swimmer had inter-cycle differences in appearance of maximum knee flexion

The between and within swimmer differences described above suggested that an analysis of the timings of MKF in all kicks for the group of swimmers would be of limited importance and usefulness. Nevertheless, for the purposes of obtaining an indication regarding the timings of one MKF, the changes in the timings of the same MKF (using the timing of MKF in SC1 as a criterion) throughout the 200 m were calculated for both the left and right knees. There were no significant changes in the timings of the left ($0.056 \leq p \leq 0.696$) and right ($0.060 \leq p \leq 1.000$) MKF for any pairs of SCs (with the exception of SC1/SC2 for the right knee, $p=0.009$). Differences in the mean values for different pairs of SCs ranged from -1.3 % to 6.2 % (individual data are shown in Table C.19, Appendix C).

5. Discussion

The purpose of this thesis was to examine the intracycle variations in kinematic parameters throughout a 200 m maximum freestyle test. Moreover, the relationships between performance and the magnitude and bilateral asymmetries of these parameters were investigated. The discussion is presented in four sections. The first section discusses briefly the changes in average V and the generic kinematic parameters that are associated with performance (SR and SL). The next three sections discuss the magnitude and the relationships with performance for the following parameters: intracycle V maxima/minima and V fluctuations; shoulder and hip roll; MEF and MKF.

5.1 Test performance, average horizontal velocity, stroke rate and stroke length

The performance times and pacing strategy (as indicated by comparison of average CM velocities for the test with elite competition data, as discussed below) for the 200 m suggested that swimmers simulated successfully a competitive race. Swimmers generally decreased average V throughout the event, with the exception of some swimmers that increased V from SC3 to SC4. The reduction in swimming V is possibly related to the aerobic/anaerobic limitations and fatigue-related changes in physiological parameters. The increase in V of some swimmers in the last 50 m of the event may be related to changes in pacing strategies. During the course of a 200 m race, swimmers would swim at sub-maximal rather than maximal pace, as the physiological effects of the latter would rapidly produce fatigue levels that could cause an early deterioration of swimming technique. Nevertheless, when the end of the race is approaching, swimmers usually switch to maximal effort and, therefore, sometimes produce higher V than in other parts of the race. The focus of this study was on changes in kinematic characteristics of swimming technique during a 200 m maximum freestyle swim, with acknowledgement of the effect of fatigue without quantifying it. Given the paucity of kinematic data in the extant literature such an investigation was warranted. With this knowledge as a foundation, future research could involve interdisciplinary approaches to examine relationships between biomechanical and physiological variables.

The magnitude of reduction in V was not related to the performance level of the swimmers. Given that all swimmers produced performances that were very close to, or even better than, their best competition performance of the year, any negative effects of training/conditioning status could have had only a small influence in the test. However, the relationship between average V and the reduction in V may be affected by factors such as individual pacing strategies. Moreover, it is possible that the range of average velocities was not large enough to provide an indication of such a relationship. Even though faster swimmers have been found to have a smaller decrease in V than slower swimmers in some previous studies (e.g. Chatard *et al.*, 2001a; 2001b), other studies have shown no differences between faster and slower swimmers (e.g. Chatard *et al.*, 2001c; 2001d). Also, the calculated reduction in V might not always represent accurately changes in performance across a race. For example, if a swimmer maintains a high average V during the first 150 m but experiences a dramatic decrease in the last 50 m of the race, then the large reduction in V from the first to the last 50 m would not fully reflect the swimmer's performance for that race.

Many researchers have calculated average V changes during 200 m freestyle events. For example, Chatard *et al.* (2001c) measured in 2D the mid-pool average V for the male 200 m freestyle final and semi-final events during the 2000 Olympic Games. The results were very similar to the present study, with swimmers decreasing average V throughout the test, with the exception of some swimmers that maintained or increased V in the last 50 m. However, Girold *et al.* (2001) reported slightly different patterns for the female 200 m freestyle event. Although the V changes of the semi-finalists were similar to those discussed above, the finalists had only minor differences (0.01 $m{\cdot}sec^{-1}$) in average V between the second, third and fourth 50 m lengths. However, it must be noted that the semi-finalists' data were obtained from a different race (semi-final, rather than final of the event) and some of the between-group differences might be related to race-specific differences in pacing strategies. The results of these race analyses suggested that pacing strategies might vary even for elite level swimmers.

The SR and SL changes in the present study were also in agreement with data reported for competitions. Similar to the study of Chatard *et al.* (2001c), swimmers in the present study had the highest SR in SC1 and the lowest SL in SC4. Changes between subsequent SCs were not always significant, but such variation in the SR and SL combinations has been frequently reported in other studies (e.g. Sidney *et al.*, 1999). The SR/SL relationship in this study confirmed the findings of existing research (e.g. Arellano *et al.*, 1994), with SR and SL having a strong negative correlation. Nevertheless, neither SR nor SL were significantly related to average V. However, this finding should not be surprising, since competition data have indicated that the influence of SR and SL in performance might vary between swimmers (e.g. Girold *et al.*, 2001; Chatard *et al.*, 2001d). Therefore, the lack of association between average V and SR/SL might be attributed to differences between the influence of these parameters on the average V of individual swimmers.

5.2 Intracycle velocity

Several authors have underlined the importance of maximum/minimum intracycle horizontal V and of the magnitude of V fluctuations in swimming performance. However, methodological limitations in previous studies have not allowed the accurate calculation of the intracycle horizontal V of the CM. Moreover, no other studies have investigated the intracycle V fluctuations for the vertical and lateral directions in any swimming stroke. Therefore, one of the main purposes of the present study was to improve understanding of freestyle swimming kinematics by calculating accurately the intracycle V in all three directions and identifying any relationships with performance.

5.2.1 Magnitude of horizontal velocity maxima and minima and relationships with performance

One of the purposes of this study was to calculate accurately the horizontal V maxima and minima and to examine whether they are associated with swimming performance. Both the maximum and minimum V were significantly higher in SC1 than the other three SCs. Minimum V was also significantly higher in SC2 than SC3. Swimming performance was associated predominantly with maximum V, as high average V was linked mainly to swimmers' ability to produce high maximum V (as indicated by the strong correlations throughout the test), rather than maintain high minimum V (strong correlations only in SC3 and SC4). Nevertheless, the stronger correlation between average and minimum V (as opposed to maximum V) in SC4, implied that (contrary to the first three SCs) during the last SC of the race swimmers maintained a high average V mainly by increasing (or minimising the reduction in) minimum V.

It would be logical to expect swimmers to produce higher maximum and minimum V at the early stages of the race. As the race progresses, the ability of a swimmer to produce high maximum V decreases due to factors such as fatigue, which would lead to application of smaller propulsive forces. It is also possible that deterioration of swimming technique would have a negative effect on the ability of a swimmer to minimise resistive forces within a SC. Furthermore, it would be reasonable to assume that SCs of smaller duration are associated with less time of application of resistive forces. Therefore, the higher minimum V in SC1 may be partially explained by the smaller duration of SC1 than the other three SCs. Nevertheless, despite the durations of SC2 and SC3 being similar, minimum V was significantly smaller in SC3, while no change was recorded for maximum V. The latter implied that a deterioration of swimming technique in SC3 affected the ability of swimmers to minimise resistive forces and/or produce high propulsive forces primarily during the slowest parts of the SC.

Minimum V and performance were not significantly correlated in SC1 and SC2. However, resistive forces (active drag) in swimming are expected to be proportional to the square of V (e.g. Toussaint *et al.*, 1988). The latter could partially explain the discrepancies (for the correlation between minimum V and performance) between the first two and the last two SCs. The high maximum velocities reached by the fastest swimmers in SC1 would generate large resistive forces, which could be associated with the large reduction in V during this SC. When the maximum V of the swimmers decreased, then the strength of the relationship between minimum V and performance increased. Therefore, the ability of faster swimmers to limit the V reduction seemed to increase with decreasing maximum/average V. The latter was confirmed by the values of the correlation coefficients (between minimum V and performance), which increased with each SC.

Moreover, it has been suggested that propelling efficiency is directly related to the power applied by the swimmers to overcome drag and give the masses of water pushed away a kinetic energy change (e.g. Toussaint & Beek, 1992). However, power is a function of V cubed (e.g. Barbosa *et al.*, 2005). Considering that the ability of a swimmer to produce high V maxima/minima is expected to be associated with their power and, therefore, the effectiveness in the application of propulsive forces and their ability to minimise resistive forces, it would be of interest to explore in future studies whether strong associations between intracycle V changes and performance exist when the V changes are normalised to take into account the non-linear relationship between V and propulsive/resistive forces. However, there is some experimental evidence suggesting that the linear approach might be a better indicator of the relationship between energy expenditure (which parallels power) and V (e.g. Barbosa *et al.*, 2005; 2006). Barbosa *et al.* (2005; 2006) stated that the higher adjustment of the linear compared to the cubic relationship could be associated to the decrease of internal mechanical work to compensate the hydrostatic torque at higher velocities and/or to an increase in efficiency with increasing V.

Other breaststroke and butterfly studies in this area have shown also that maximum and minimum velocities are associated with performance, with faster swimmers reaching higher V maxima/minima than slower swimmers (e.g. Manley & Atha, 1992; D'Acquisto & Costill, 1998; Takagi *et al.*, 2004). Nevertheless, the magnitude of V maxima/minima has not been reported in other freestyle or in backstroke studies. Lower V minima/maxima have been reported in the literature for breaststroke and butterfly (with the exception of maximum V in butterfly) than the freestyle values found in the present study. Sanders (1996a; 1996b) reported instantaneous velocities ranging from 0.52 to 2.33 $m \cdot sec^{-1}$ for butterfly and from 0.45 to 1.77 $m \cdot sec^{-1}$ for breaststroke (0.97 to 2.20 $m \cdot sec^{-1}$ for freestyle in the present study). Higher maximum V in freestyle than breaststroke/butterfly is expected as the propulsive phases of the arms overlap (i.e. one arm starts pulling before the opposite arm exits the water) and, together with the leg actions, maintain continuity in the production of propulsive forces. However, in butterfly and breaststroke both arms recover at the same time and both legs kick simultaneously. Thus, phases with small or zero propulsive forces during certain parts of the SC would result in low minimum velocities.

Similarly, larger maximum intracycle velocities in butterfly could be expected due to higher propulsive forces produced when both arms and legs contribute to propulsion (as opposed to freestyle). Nevertheless, these propulsive forces are applied simultaneously only for a small period of time during a SC. Considering that these forces need to accelerate a swimmer's CM that has probably reached a smaller minimum V than in freestyle, the maximum V will be dependent on several factors, such as magnitude and duration of application of propulsive forces. Taking into account possible differences in the level of swimmers between the above studies and that bilateral symmetry was assumed for the butterfly analysis, one cannot state with confidence that maximum intracycle horizontal V in butterfly is expected to be higher than in freestyle. An analysis on participants of the same level who would be tested with the same research protocol might be informative with regards to differences in instantaneous V and magnitude of V fluctuations between these strokes.

5.2.2 Magnitude of velocity fluctuations

5.2.2.1 Fluctuations in all directions and relationships with performance

V fluctuations in the horizontal direction are expected due to the variation in the magnitude and direction of forces during a SC. Fluctuations in vertical and lateral V would be caused by resultant propulsive and resistive forces having components other than along the horizontal line in the direction of intended travel. Fluctuations in vertical V can also be due to changes in the relative magnitude of the buoyancy and gravitational forces. Therefore, fluctuations in vertical and lateral V occur as segment movements within a SC constantly change the magnitude and direction of the forces acting on the swimmer. The movements of the segments are associated with the swimmer's attempts to generate propulsion and to maintain the most efficient hydrodynamic position.

Even though one would expect some V fluctuations in directions other than the horizontal, it is probably surprising that noteworthy fluctuations of the magnitude of 0.40 m·sec^{-1} (26.25 % of average horizontal V) and 0.54 m·sec^{-1} (35.37 % of average horizontal V) were calculated for the lateral and vertical V of the CM for the 200 m. These values were close to the horizontal V fluctuations (0.65 m·sec^{-1} or 42.81 % of average horizontal V). The mean 200 m values indicated that large fluctuation values in one direction were associated with large fluctuation values in the other two directions. Nevertheless, the correlations for each SC showed a high variation in the strength and significance of the relationships between fluctuations in different directions, suggesting that the magnitude of V fluctuation in one direction is not always strongly associated with the magnitude of fluctuation in another direction.

One of the main purposes of this study was to examine the extent to which the magnitude of intracycle V fluctuation was linked to performance. It was shown that the absolute and percentage V fluctuations in all directions were not associated with performance (as indicated by average V). However, high maximum intracycle velocities were associated with large horizontal fluctuation values in most SCs. High minimum velocities were positively associated only with percentage horizontal fluctuations and only for two SCs. As discussed above (section 5.2.1) large V maxima would be expected to generate large resistive forces, which could cause large reduction in V and, thus, large intracycle V fluctuation. The latter could partially explain the positive relationships found for horizontal V fluctuations and V maxima in most SCs.

The results of this study were not in agreement with previous studies, which reported that faster swimmers had smaller horizontal V fluctuations (e.g. Togashi & Nomura, 1992; Sanders, 1996a; 1996b; Takagi *et al.*, 2004). A possible explanation could be that previous studies examined the V fluctuations in breaststroke and butterfly only. Considering the larger range of V fluctuations in these strokes, it might be possible that the expected relationship was not found in freestyle due to the smaller range of V fluctuations or due to differences between breaststroke/butterfly and freestyle in the propulsive and resistive periods of the SCs. Moreover, the limitations of previous studies in this area, such as the use of the hip or the bilateral symmetry assumption for V calculations (see section 2.2.3), might also be associated with the disagreement in the findings.

Similar to the discussion for the relationship between performance and V maxima/minima, it is also possible that the relationship between V fluctuation and average V does exist but is not linear. For example, in a recent study by Barbosa *et al.* (2006) it was reported that the polynomial produced a better adjustment than the linear approach for the relationship between V fluctuation and average V. Nevertheless, despite the significant correlations found in all strokes ($p \leq 0.05$) except breaststroke ($p=0.06$), the calculated coefficients did not show a very strong relationship ($0.47 \leq r \leq 0.65$). These investigators stated that the parabolic curve could possibly be explained by the curve between force and V for neuromuscular activity. Barbosa *et al.* added that the data suggested that the neuromuscular activation of several muscles in a multi-segment and multi-joint movement follows the force-velocity relationship pattern for a single joint system. However, it must be noted that the study design was different to the present study. Barbosa *et al.* (2006) tested 4-5 swimmers on each stroke for a range of incremental velocities, and performed the statistical analysis on each stroke after pooling the data of all the tests for each swimmer.

The fluctuations in the V of the CM are directly related to the V maxima/minima reached by the swimmers. As discussed in section 5.2.1, the maximum and minimum velocities reached during a SC are affected by the resistive and propulsive forces, which are expected to have a non-linear relationship with V. Therefore, it would be of interest to explore in future studies whether V fluctuations are associated with average V in a non-linear manner. Moreover, the resistive forces experienced during a SC are influenced by a number of factors, such as the cross-sectional area exposed to flow, the V of body segments in the direction of travel and the alignment and shape of body segments (Sanders, 2002). Therefore, the influence of these factors on the magnitude of intracycle V fluctuations could also be explored, as it could improve further the understanding of the causes of V fluctuations during a SC.

The present study also showed that there were some between and within swimmer variations in the magnitude of fluctuation for a given V. It would be reasonable to assume that swimming with less V fluctuations for a given average V would be more economical and require less energy expenditure. Thus, it would be of interest to identify the differences in the kinematic characteristics between SCs of different fluctuations for a given average V. Such information would be useful for swimmers and coaches as it could provide a guidance for the most effective technique for a given V, minimising therefore the energy demands. Finally, it must be noted that the swimmers participating in this study were tested during the middle part of the season. A longitudinal study throughout the season would also be of interest, as it would allow the investigation of the influence of training and/or conditioning status on any changes in the efficiency of swimmers' technique.

The magnitude of horizontal V fluctuations has not been calculated for freestyle and backstroke. Nevertheless, horizontal V fluctuation values have been reported in some butterfly and breaststroke studies. For example, Sanders (1996a; 1996b) found V fluctuations that ranged from 0.92 to 1.40 $m \cdot sec^{-1}$ (56.8 to 106.1 % of average V) for butterfly and from 0.76 to 1.12 $m \cdot sec^{-1}$ (60.3 to 95.7 % of average V) for breaststroke swimmers (0.40 to 0.96 $m \cdot sec^{-1}$ or 27.1 to 64.4 % for freestyle in the present study). In general, intracycle V fluctuations reported in the breaststroke and butterfly literature were larger than those calculated for freestyle in the present study. As discussed above (section 5.2.1), it would be reasonable to expect larger fluctuations in butterfly/breaststroke than in freestyle, due to the differences in the propulsive actions of arms and legs and the resistive forces experienced during the SC.

Although fluctuations in the lateral and vertical directions have not been considered as being very important (given the lack of attention to these parameters in swimming texts and the fact that they have not been calculated for any stroke), this study indicated fluctuations of considerable magnitude for both directions. Despite these fluctuations not being significantly correlated with performance, future research needs to investigate more closely the causes of these fluctuations and the possibility of a non-linear relationship between lateral/vertical fluctuations and average V. Identification of the influence of such fluctuations on swimming kinematics could provide important information to swimmers and coaches that would facilitate the improvement of swimming performance.

5.2.2.2 Changes throughout the test

The present study was the first to test V fluctuation changes across an event. The results indicated that horizontal fluctuations were significantly higher in SC3 than in SC2 and SC4. On the contrary, fluctuations in the lateral/vertical directions remained constant throughout the test. Therefore, the high increase in horizontal V fluctuation in SC3 was not associated with similar changes in the other directions. Moreover, the changes recorded for horizontal fluctuation in SC3 were not linked to changes in SR, SL or SC time.

As discussed in section 5.2.1., there were no changes in maximum V between SC2 and SC3, but there was a significant decrease in minimum V, implying that the ability of swimmers to minimise resistive forces and/or produce high propulsive forces (in SC3) decreased mainly during the slowest parts of the SC. Although maximum V decreased subsequently in SC4, swimmers increased minimum V reducing, thus, the overall fluctuation. The latter phenomenon could be associated with pacing-related technique strategies (e.g. swimming SC4 at maximum effort due to it being in the last 50 m of the race, as opposed to saving energy during SC3). However, it is also possible that swimmers were able to maintain higher minimum V in SC4 because the resistive forces causing the reduction in V were smaller in magnitude than in SC3 (due to lower maximum velocities achieved).

5.2.3 Velocity patterns and timing of appearance of horizontal V maxima and minima

The intracycle V patterns differed between the horizontal, lateral and vertical directions. The horizontal V had two distinct maxima and in the majority of the cases minima in each SC, with one maximum and one minimum value associated directly with the left and right arm UWPs. In contrast to the patterns for horizontal V, no distinct pattern existed with regard to the timing or the number of maxima and minima for vertical and lateral intracycle V. For all directions, intracycle accelerations/decelerations resulted in several V increases/decreases of smaller magnitude, which varied between and sometimes within swimmers.

Despite methodological limitations, previous swimming studies have provided some indication of V patterns in all four strokes. In the only other study describing freestyle V patterns, Maglischo *et al.* (1989) also identified distinct maxima and minima for the horizontal V. Despite some similarities with the patterns reported in the present study, the qualitative analysis of the former study did not involve further investigation on the timing of appearance of V maxima/minima during the SC. Backstroke swimmers seem to have similar V patterns with freestyle swimmers, with distinct V maxima and minima associated possibly with the UWPs of the arms (e.g. Maglischo *et al.*, 1989). Butterfly swimmers appear to reach maximum V during the first or the second kick, with breaststroke swimmers reaching maximum V during the pull phase of the arms or after the first kick (e.g. Sanders, 1996a; 1996b). In view of the findings of the present study and the advances in swimming analysis methods, researchers should be encouraged to calculate accurately the intracycle V patterns of backstroke, butterfly and breaststroke in all three directions (in consideration with the associated swimming actions) to improve the understanding on these strokes.

5.2.3.1 Analysis of the timings and association with body segment positions

This study contributed to the improvement of the understating of freestyle swimming by identifying the timing of V maxima/minima in a SC and their association with the positions of body segments. It was shown that swimmers produced maximum intracycle V when the arm that contributed to propulsion was at the first half of the UWP, with the hand moving downwards and backwards (elbow ahead of shoulder on the horizontal axis). At this time the opposite arm (being at the early parts of the recovery phase) did not contribute to propulsion. Minimum intracycle V occurred when the arm was at the second half of the UWP, while the hand was moving backwards and upwards (elbow behind the shoulder on the horizontal axis). At the same time, the opposite arm was either at the end of the recovery phase (before entering the water) or at the glide phase of the UWP (hand gliding forward without applying any propulsive forces), before performing the 'catch'. It was also shown that freestyle swimmers reached maximum V at the same part of the SC that they had maximum shoulder and hip roll values. Moreover, it was noted that the MEF and minimum V occurred at the same part of the SC.

The calculation of intracycle horizontal V of the CM provides an indication of the net force associated with parts of the SC. When V increases, the propulsive forces are higher than the resistive forces, while the opposite is true when V decreases. Considering that resistive forces are expected to increase proportionally with the square of V, the appearance of V maxima coincided with the largest resistive forces experienced by the swimmer during the SC.

As discussed above, minimum V occurred at the same part of the SC as MEF. The latter implied that the positioning of the elbow relative to the body might be more effective (with regard to the production of propulsive forces) after the point of MEF, when the hand moves backwards and upwards and the elbow is extending. It is also possible that the larger cross-sectional area exposed to the flow at this part of the SC (as both arms are in the water) is associated with higher water resistance. However, despite the emphasis that has been given by some researchers to the positive relationship between the magnitude of MEF and swimming performance, MEF did not appear to be a factor of differentiation between faster and slower swimmers (as discussed in section 5.4.1.2). Nevertheless, this should not be interpreted as that the MEF is not important for successful performance in freestyle. Although MEF is not linked to the production of high net forces in a SC as it occurs at the same part as V minima, this study showed that faster swimmers are in some cases characterised by higher minimum V than slower swimmers, with this relationship becoming stronger as the race progressed. The latter finding emphasised that swimmers can improve performance by maximising propulsive forces (and minimising resistive forces) when the elbow is close to maximum flexion, as this would minimise the reduction in V and fluctuation of V and, therefore, facilitate the improvement of performance. Given that V minima of similar magnitude appeared in other parts of the SC for some swimmers, the degree of association of arm strength with the production of maximum/minimum V could also be investigated by including measurements of arm strength for the positions of interest.

Considering that V maxima coincided with hip/shoulder roll maxima (and that after this point in the SC resistance was greater than propulsion), it is possible that the change in direction of shoulder/hip roll was associated with resistive forces on the vertical and lateral directions, which could have influenced the V of the CM.

Further parameters that might be related to the magnitude and timings of intracycle V maxima/minima include among others: the hand V and orientation throughout the UWP of the stroke; the rotational movements and the angular V of the elbow and the wrist; the vertical and horizontal displacement of the shoulder, elbow and wrist joints; the propulsion generated by the kicking actions etc.

As discussed above, the net force is dependent on the relationship between propulsive and resistive forces, with the intracycle V analysis providing an indication of the balance between these forces. Exploration of the acceleration data could be informative in improving the understanding of the relationships between propulsive and resistive forces, by enabling the identification of the extent to which certain phases of the SC are propulsive. Analysis of acceleration data was beyond the scope of this thesis. Nevertheless, for the purpose of providing an indication of such data and facilitating the discussion of the net force patterns, the acceleration of the CM was calculated for the fastest and the slowest swimmer of this study. Figures 5.1 and 5.2 show the V and acceleration of each swimmer during SC1. Figures 5.3 and 5.4 show the acceleration for each swimmer throughout the four SCs.

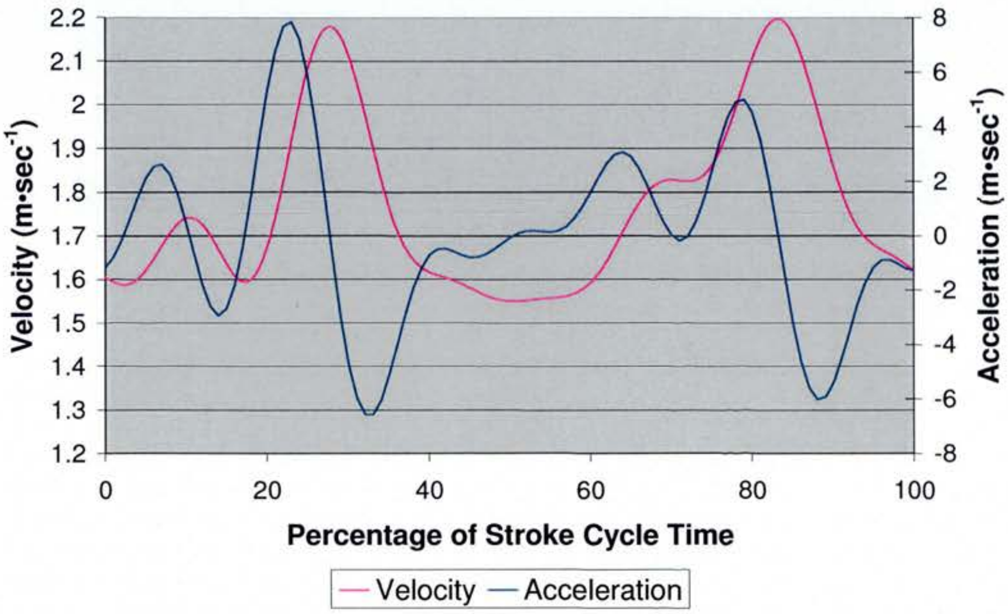

Figure 5.1: Pattern of horizontal V and acceleration of the CM during SC1 for swimmer 1

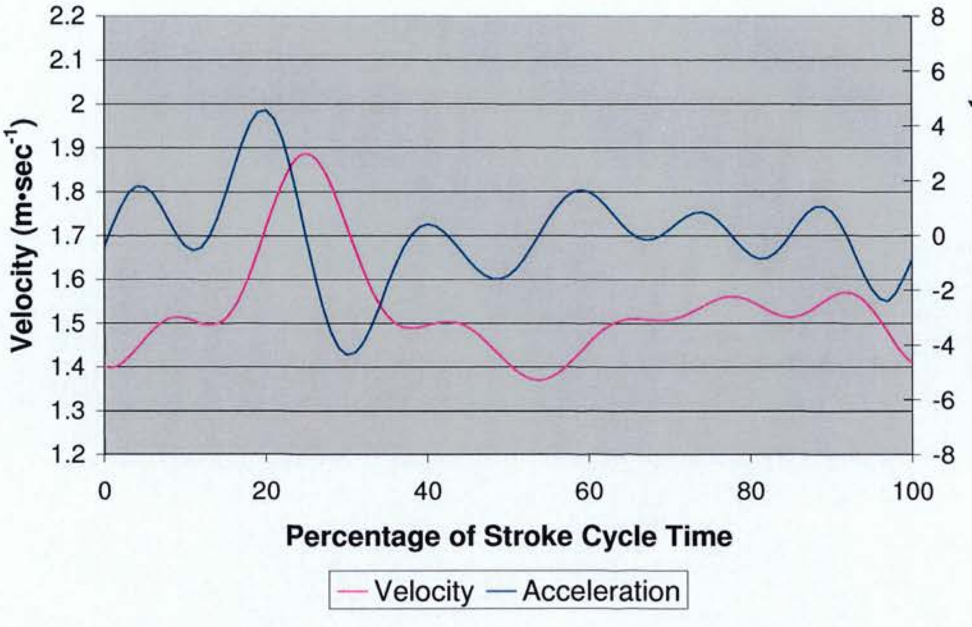

Figure 5.2: Pattern of horizontal V and acceleration of the CM during SC1 for swimmer 11

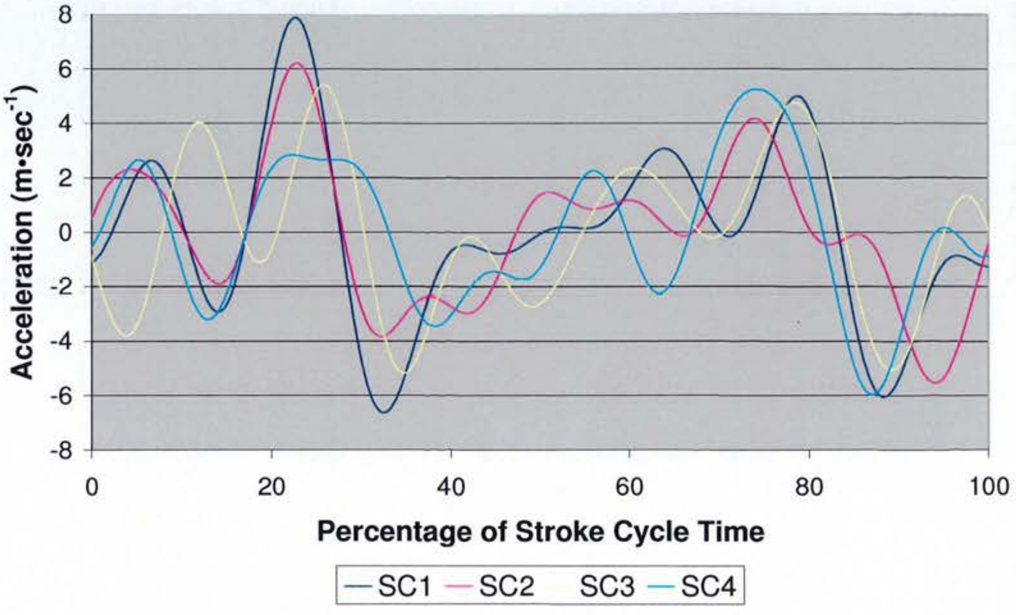

Figure 5.3: Pattern of horizontal acceleration of the CM for swimmer 1

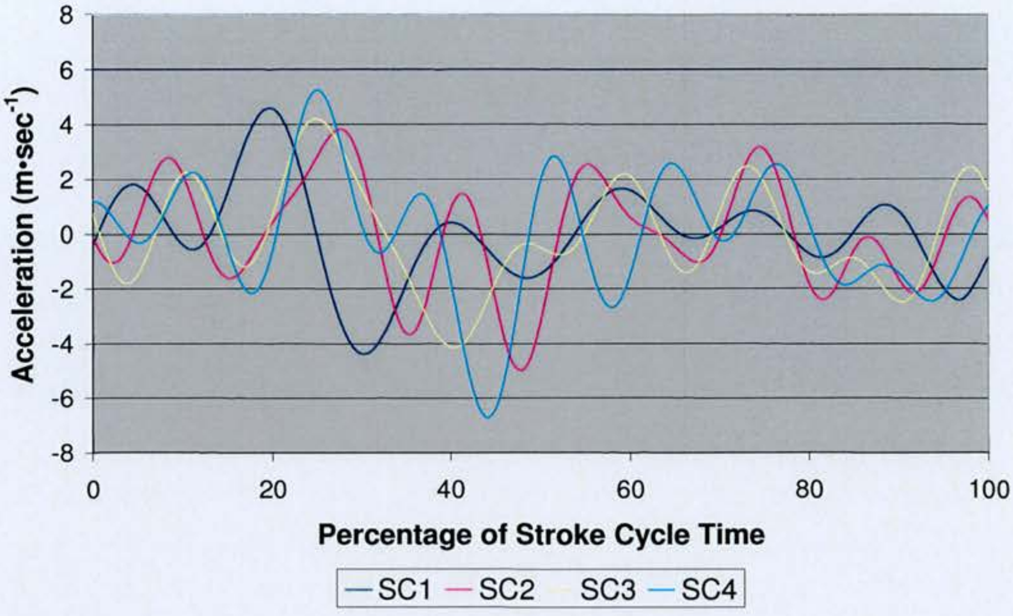

Figure 5.4: Pattern of horizontal acceleration of the CM for swimmer 11

The intracycle acceleration pattern for swimmer 1 had four distinct maxima and four distinct minima. The analysis of the performance of swimmer 1 and the data in Figure 5.1 showed that the first maximum value of acceleration occurred shortly after hand entry and while the opposite hand was moving backwards and upwards. This suggested that the opposite arm might be effective in the production of propulsive forces at this position. However, in freestyle swimming, the hand usually enters the water before the elbow and shoulder. Therefore, the submersion of the elbow and shoulder (and the associated resistance) may be related with the decrease in acceleration after the first peak.

The first minimum value of acceleration (maximum deceleration) was recorded approximately at the instant of 'catch' (opposite hand still moving backwards and upwards). No propulsive forces are applied by the swimmer's arm when the hand is gliding forward (between hand entry and 'catch'). Given that at the period between the first maximum and minimum accelerations both arms were in the water, the deceleration could be linked to the increased cross sectional area exposed to flow which would be expected to increase water resistance.

The second (greater in magnitude than the first) maximum acceleration value occurred after the 'catch' (while the hand was moving backwards and downwards) and just before the opposite hand exited the water. This is reasonable, since both arms were contributing to propulsion. In addition, considering that the opposite shoulder started the recovery phase before the hand, it is possible that the smaller cross-sectional area of the swimmer (as one shoulder was above the water) was associated with a more hydrodynamic shape and resulted in smaller resistive forces (as opposed to both shoulders being in the water). These findings suggest that swimmers could increase the maximum V by extending the length of the period that both arms contribute to propulsion. This could possibly be achieved by an earlier 'catch' and by ensuring that the hand continues its backwards movement in the water until the arm is fully stretched.

The second minimum acceleration value was observed when the hand was still at the first half of the UWP, moving downwards and backwards. At the same point, the opposite arm was at the middle of the recovery phase. Given that in the periods before and after the second minimum acceleration the opposite arm is recovering, it is possible that the pulling arm is not very effective in the application of propulsive forces in the associated positions (and/or the swimmer is not very effective in minimising resistive forces). The shift in the acceleration curve at that point (maximum deceleration) may be partially explained by the change in the position of the recovering arm, which could have contributed to the forward shift of the CM. Finally, after the entry of the opposite hand the acceleration patterns were similar to those described above.

A comparative evaluation of Figures 5.1 and 5.2 suggested that the slowest swimmer, despite having a similar pattern to the fastest swimmer during the first half of the SC, had a different pattern during the second half of the SC. The slowest swimmer didn't replicate the pattern of the first half during the second half of the SC, with the maximum and minimum acceleration being smaller in magnitude and less distinct than in the first half. This suggested that the number and magnitude of changes in acceleration (and, therefore, the balance of propulsive and resistive forces) might be related to swimming performance. However, it must be noted that patterns similar to those of swimmer 11 were also observed for faster swimmers (e.g. swimmer 5, as shown in Figure 4.3, section 4.3.1.1). Moreover, Figures 5.3 and 5.4 suggested that the number and magnitude of changes in V and acceleration might change during a race. Therefore, it would be of interest to conduct further analysis in order to assess whether such differences exist between faster and slower swimmers and if they change during a course of the race.

Figures 5.1 and 5.2 also showed that swimmer 1 had much higher acceleration and deceleration values than swimmer 11 in SC1. This indicated that swimmer 1 was producing larger propulsive forces (and/or was able to minimise resistive forces) during the propulsive parts of the stroke. Nevertheless, the larger resistive forces created from the higher velocities achieved by swimmer 1, resulted in a much greater deceleration of the CM (during the slowest parts of the SC) than swimmer 11. However, Figures 5.3 and 5.4 suggested that the ability of the faster swimmer to minimise the V reduction improved in SCs 2, 3 and 4. Indeed, swimmer 11 experienced a greater deceleration (despite reaching much lower maximum V) than swimmer 1 in SC4. These patterns were in agreement with the correlations between performance and minimum V (discussed in section 5.2.1), which indicated that the ability of faster swimmers to limit the decrease in V improved for lower velocities.

Although some investigators have attempted to calculate the acceleration of the hand (e.g. Rouboa *et al.*, 2006), accurate 3D data on the acceleration of the CM have not been reported. In the above discussion, an association of the intracycle maxima/minima in the net forces (as indicated by acceleration data) with the movements of the arms and the trunk was attempted. Moreover, a qualitative evaluation of acceleration data of the fastest and the slowest swimmer throughout the 200 m was attempted, for the purpose of obtaining an indication of possible differences in acceleration patterns. However, the net force is influenced by other parameters, such as the timing and duration of application of propulsive forces, the segment positions and orientation, the propulsive actions of the legs and changes in the shape of the body (streamlined or not-streamlined) caused by factors such as the vertical movements of the head. Considering that the acceleration data can provide further information with respect to specific changes in net forces occurring during a SC, future analyses should explore the intracycle acceleration patterns (e.g. magnitude and duration of accelerations) and examine their association with swimming performance.

5.2.3.2 Changes throughout the test

There were no clear trends between faster and slower swimmers with regard to the timing of appearance of V maxima/minima in a SC. However, some V maxima and minima occurred earlier in SC1 than the following SCs. In view of these changes, a subsequent analysis of the relative timings of the underwater and recovery phases was conducted for each SC. This showed that, in general, the relative duration of the left arm UWP (and, therefore, the ratio between the duration of the UWP and the recovery phase) was significantly less in SC1 than in the other three SCs (see Table D.1 Appendix D). Despite the duration values for the right arm UWP being of similar magnitude to those for the left arm, there were no significant differences between the SCs, possibly due to high between swimmer variability. Nevertheless, these results suggested that swimmers were spending less time for the UWP of the stroke in SC1 than in the other three SCs. Therefore, the observed shifts in some V maxima and minima may be partially explained by the changes in the relative durations of the aforementioned phases.

The reasons that changes in the duration of stroke phases did not affect significantly all intracycle V minima/maxima remain to be investigated. For future research, the analysis of two consecutive SCs is suggested, as it will enable calculation of the timings of V maxima and minima relative to each arm's UWP. This would allow investigators to examine whether any changes are related to the increase in the relative duration of the UWP of each arm. If similar changes exist in the appearance of V maxima and minima relative to the UWP each arm, then the influence of other parameters should be considered. For example, although the separation of the UWP of the stroke into different phases was beyond the scope of this thesis, it was observed that some swimmers tended to spend more time between hand entry and 'catch' as the race progressed. The latter would delay the initiation of the application of propulsive forces (and extend the period of application of resistive forces) and could be associated with changes in the relative timings of V maxima and minima. Therefore, another focus of future studies could be the separation of distinct parts of the UWP of the stroke and the comparative analysis of the variation in kinematic parameters between these parts.

5.2.4 Bilateral asymmetries

Qualitative analyses have indicated the existence of bilateral asymmetries in V patterns. The present research attempted to advance the existing knowledge by quantifying the bilateral asymmetries in intracycle V and identifying the underlying relationships. The analysis of V minima/maxima and V fluctuations for the UWP of the left and the right arms indicated asymmetries in all parameters. Nevertheless, the magnitude of bilateral asymmetries was not associated with the performance level of the swimmers. High V maxima for the left were associated with high V maxima for the right side, but no similar relationship existed for the V minima or V fluctuations. Moreover, V maxima for each side were not associated with V minima for the same side. As discussed in section 5.2.1, these findings could possibly be explained by the larger forces created for higher V maxima, which seem to cause a large reduction in intracycle V.

Interestingly, with the exception of one swimmer who presented overall symmetry, all swimmers reached higher maximum V during the UWP of the right arm. Although, no consistent side bias was found for the asymmetries in V minima and fluctuations, most swimmers that presented lateral dominance (in any of the above parameters) maintained the dominant side throughout the 200 m. Although the study design did not include any upper limb strength or skill-related measurements, personal communication with the swimmers revealed that all participants were right handed. Therefore, it is possible that the left arm was not as effective as the right arm during the propulsive phase of the stroke, resulting in lower maximum V. For the purposes of testing the latter hypothesis and identifying the cause of such asymmetries, a future study could examine the differences between groups of left and right handed swimmers. Strength measurements of the upper limbs might also be informative with regard to the extent that possible asymmetries are associated with the strength of the arms. Nevertheless, dry-land strength is not always translated into effective swimming technique, and asymmetries might be dependent on other factors such as effectiveness of the application of propulsive forces by the arms, body position and propulsive forces of the legs. Finally, further analysis of data of the present study could also be informative in terms of technique differences that might have caused the asymmetries. Hand V and arm orientation during the UWP of the stroke are some of the parameters that could improve the understanding of the cause of these asymmetries.

The present study provided a strong indication that the swimmer applies greater force with the dominant arm and/or possibly adopts such a body position that minimises the resistive forces. Even though bilateral asymmetries were not associated directly with performance, it would be reasonable to assume that if a swimmer manages to produce maximum V of equal magnitude during the UWP of the non-dominant arm, then the average V of the SC would increase, providing that the swimmer would be equally effective in minimising the resistive forces during the UWP of the non-dominant arm. A separate analysis of the UWP of each arm would be illuminating with regard to differences in average V between the UWPs of the two arms.

The changes across the test in V maxima/minima/fluctuations for the left and the right arm UWPs were in general similar to those for the overall values. However, the results showed that the significant decrease in overall minimum V and V fluctuation in SC3 was linked to a significant decrease of the same values for the left arm UWP, while the values for the right arm UWP did not change. Moreover, the V maxima for the left and right arms did not change significantly between SC2 and SC3. These findings suggested that the technique deterioration in SC3 was associated predominantly with a decrease in the ability of swimmers to produce high propulsive forces and/or minimise the effect of resistive forces during the slowest part of the UWP of the non-dominant arm. The above changes in the V minima may also be related to changes in the timing and/or the duration of application of propulsive forces by the swimmers.

The above findings underlined the importance of technique improvement on the non-dominant side of the swimmers. Therefore, coaches could focus on additional strength and endurance training on the non-dominant arm. Despite the present study restricting the analysis to non-breathing SCs, it would be reasonable to expect bilateral asymmetries of similar or higher magnitude during breathing cycles. Therefore, swimmers and coaches should give emphasis not only to ensuring similar strength, endurance and flexibility between the left and right sides, but also to establishing bilateral symmetry in swimming technique during both breathing and non-breathing cycles.

5.3 Kinematic parameters of the trunk: shoulder and hip roll

A main purpose of this study was to calculate accurately the shoulder and hip roll to the left and the right sides of competitive swimmers throughout the course of a race. Moreover, this research aimed to examine whether the magnitude of roll and/or asymmetries in roll were associated with swimming performance.

5.3.1 Roll patterns and timing of roll maxima

The results showed that both shoulders and hips had two distinct maxima corresponding to maximum roll to the left and right sides. In general, the shoulders and hips rolled towards the same direction during the SC. Moreover, the timings of shoulder and hip roll maxima (indicating a change in rolling direction) had no significant differences during the test. It must be noted that these patterns represent non-breathing SCs. However, there are some indications in the existing literature that breathing patterns might affect the rolling actions of the trunk in freestyle swimming (e.g. Payton *et al*., 1999b; Castro *et al*., 2003). Therefore, it would be of interest for future studies to assess the influence of breathing actions on the rolling patterns of shoulders and hips.

The calculations of the timings of shoulder and hip roll maxima showed that all maxima occurred significantly earlier in SC1 compared to the other three SCs. As discussed in section 5.2.3.2, the relative duration of the UWP of the stroke and the overall SC time were significantly lower in SC1 than SCs 2, 3 and 4. Thus, the later appearance of roll maxima could be associated with the longer relative duration of the UWP of the stroke and the longer time spent for SCs 2, 3 and 4. There was no indication of differences between faster and slower swimmers in the timings of shoulder/roll maxima. Finally, the present study showed that the timings of shoulder/hip roll maxima occurred at the same part of the SC as maximum V. This phenomenon was discussed in section 5.2.3.1.

Similar roll patterns have been found in some previous studies. For example, Yanai (2001) reported sinusoidal patterns and nearly equal phase angles for shoulder and hip roll of university swimmers tested at sub-maximal V. Cappaert *et al.* (1995) also reported that elite swimmers rolled the shoulders and hips towards the same direction during a 100 m freestyle race. However, subelite swimmers rolled the shoulders and hips in opposite directions. Personal communication with the main investigator of the latter study revealed that subelite swimmers were selected on the basis of the poorest technique, with many of them participating in the Olympic Games due to countries' entitlement of entering a small number of participants with no requirement for achieving the qualification time. Cappaert stated that the status of these swimmers could be considered much lower than competitive swimmers. Therefore, the opposite rolling directions for the shoulders and hips of subelite swimmers could possibly be explained by the low performance level of that group. Presumably, subelite swimmers expected that the opposite rolling directions would provide a more balanced body position throughout the SC. Finally, similar patterns were reported by Cappaert *et al.* (1996) for some female backstroke swimmers, with elite swimmers rolling shoulders and hips towards the same direction and subelite swimmers having opposite directions for shoulder and hip roll.

5.3.2 Magnitude of roll, changes throughout the test and relationships with performance

A number of experimental studies in this area (e.g. Liu *et al.*, 1993; Payton *et al.*, 1999a; Castro *et al.*, 2003) have calculated the body roll for the whole trunk. However, in agreement with other studies (e.g. Cappaert *et al.*, 1995; Yanai, 2001), this study confirmed that freestyle swimmers have shoulder and hip roll values of considerably different magnitude, as swimmers were found to roll the shoulders about twice as much as the hips. Considering the increased accuracy of the 3D methods used in the present study, these findings indicated that the measurement of body roll for the whole trunk does not represent with validity the rolling characteristics of the trunk.

There was no clear indication that the magnitude of shoulder/hip roll was associated with the performance level of the swimmers, as no significant relationships were found for the vast majority of the correlations between shoulder/hip roll and average V. However, even though swimmers maintained the shoulder roll values throughout the test, they rolled their hips significantly less in SC1 (where V was significantly faster) than the other three SCs. It was also shown that there was a tendency for swimmers with large shoulder roll values to have large hip roll values. Moreover, swimmers with large shoulder/hip roll values for the left side sometimes presented large shoulder/hip roll values for the right side. Nevertheless, neither of the last two trends presented consistently strong relationships throughout the 200 m.

Cappaert *et al.* (1995) stated that body roll might decrease active drag by reducing the frontal surface area. Thus, large differences in the magnitude of shoulder and hip roll would increase the frontal surface are and create large resistive forces. In view of the fact that the increase in hip roll throughout the test resulted in smaller differences between the magnitudes of shoulder and hip roll, it appears that freestyle swimmers tended to roll to more hydrodynamic positions as the race progressed. The increase in SC time after SC1 might have facilitated the additional hip roll of the swimmers.

Swimmers are often instructed to increase the magnitude of roll for the purpose of improving performance. However, the present study found no strong indication of significant differences in the magnitude of roll between faster and slower swimmers and, moreover, swimmers were generally rolling the hips less when swimming faster. In line with the latter, Yanai (2001) stated that the recommendation for increased body roll seems paradoxical, as a complex mechanical association with propulsion (which will be hard to accomplish without reducing V) would be required for a swimmer to increase body roll at a given speed. Yanai added that such mechanical propulsion would include arms and legs producing forces in non-propulsive directions, thus reducing the efficiency of propulsive forces at the swimming direction. Therefore, if positions of greater magnitude in hip roll are found to be more effective in terms of minimising resistive forces (due to smaller differences in the magnitude of shoulder and hip roll), swimmers could be instructed to try to achieve such positions perhaps by using the highest possible SL for a given V, rather than increasing the forces applied to non-propulsive directions. However, an increase in SL for a given V would probably be associated with an increase in SC time. Therefore, swimmers should practise maximising the SL for a given V by extending the time of the most propulsive parts of the SC, such as the parts when both arms contribute to propulsion.

Previous studies showed that swimmers had less roll in hips (Cappaert, 1999) and shoulders (Yanai, 2001) when tested in faster velocities. Even though the hip roll calculations across the test in the present study were in agreement with Cappaert's study, the shoulder roll changes and the correlations of shoulder/hip roll with average V did not show any significant relationships. A possible explanation could be that the range of velocities in the present study was smaller than that in the study of Cappaert. In addition to this, all the calculated correlation coefficients between shoulder/hip roll and V were negative (with only two significant values), implying that there might be an underlying relationship (similar to the one reported in the former studies) between V and the magnitude of shoulder/hip roll. Cappaert (1999) compared sprint (200 m and below) and distance freestyle swimmers (above 200 m). Therefore, if swimmers are tested in different events it might be possible that relationships between performance and the magnitude of roll would exist. Yanai (2003) compared a moderate ($1.3\ m \cdot sec^{-1}$) with a sprint pace ($1.6\ m \cdot sec^{-1}$), suggesting that there might be similar relationships if a group of swimmers is tested in moderate and maximum velocities. Nevertheless, discrepancies between the above studies and the present investigation might also be partially explained by methodological limitations of these studies (as discussed in section 2.3.1.4).

Separate shoulder and hip roll values have been reported in two other freestyle studies (Cappaert *et al.*, 1995; Yanai, 2001). Both the shoulder ($35.4 \pm 2.5°$ for elite and $34.4 \pm 1.7°$ for subelite swimmers) and hip roll values ($8.3 \pm 1.5°$ for elite and $-17.8 \pm 1.5°$ for subelite swimmers) reported by Cappaert *et al.* (1995) were much lower than those found in the present study (shoulder roll: $49.2 \pm 5.3°$ for the right and $56.3 \pm 4.5°$ for the left side; hip roll: $25.7 \pm 5.7°$ for the right and $24.3 \pm 7.7°$ for the left side). On the contrary, Yanai (2001) reported shoulder roll values (mean value of 58°, confidence intervals: 52 - 65°) that were close to the higher values recorded in the present study, with the hip roll values (mean value of

36°, confidence intervals: 29 - 43°) being clearly higher than those in the present study.

The discrepancies observed between studies in the magnitude of roll could be attributed to a number of factors, such as: the level of the swimmers tested; the velocities of the tests; the influence of breathing actions (not accounted in other studies) and errors caused by methodological limitations of the studies. Nevertheless, the subelite swimmers in the study by Cappaert *et al* (1995) had similar shoulder roll range to the elite swimmers. Moreover, the participants in Yanai's study appeared to achieve velocities (mean: 1.6 $m \cdot sec^{-1}$) within the range of the velocities calculated in the present study (1.37 to 1.77 $m \cdot sec^{-1}$). However, even for horizontal velocities of similar magnitude, participants of different levels could be expected to have differences in kinematic characteristics of their swimming technique.

As discussed in section 5.2.3, future research could adopt a kinetic approach and examine the extent to which changes in shoulder/hip roll are associated with changes in the amount of propulsive and resistive forces. Furthermore, other factors such as the effectiveness of arm forces at different rolling positions and the influence of these positions on the orientation and application of kicking forces should also be considered.

5.3.3 Bilateral asymmetries

The qualitative analysis of Arellano *et al.* (2003) provided an indication of body roll asymmetries in freestyle swimming. Despite the findings of Arellano *et al.* and other research evidence on technique asymmetries (e.g. Maglischo *et al.*, 1989; Keskinen & Keskinen, 1997) the roll values for the left and right sides have not been calculated separately. This study attempted to advance the scientific knowledge by examining the shoulder and hip roll for both sides and quantifying the bilateral asymmetries. There were noteworthy bilateral asymmetries of up to 25.4° for shoulder (mean: 7.8 ± 4.6°) and 13.4° for hip roll (mean: 5.6 ± 3.8°), emphasizing further the need for calculation of these kinematic parameters for both the right and left sides. Nevertheless, the magnitude of asymmetries was not associated with swimming performance.

This study also indicated left side dominance in shoulder roll, as all swimmers presented larger shoulder roll values to the left (with the exception of one swimmer that had overall symmetry). There was no consistent side bias in hip roll. The left side dominance in shoulder roll might be related to the handedness of swimmers. Since all swimmers participating in this study were right handed, it is possible that higher flexibility and/or coordination in the right shoulder joint was associated with larger vertical range of motion of this joint during the UWP of the stroke (and therefore deeper pulling patterns), resulting to the calculated asymmetries. Future research should include upper limb flexibility, strength and coordination measurements, for the purpose of assessing their interrelationships with bilateral asymmetries in shoulder roll values and other related kinematic parameters, such as the shoulder vertical displacement during the UWP of the stroke.

Maximum shoulder roll to the left side occurred during the UWP of the right arm and coincided with the appearance of maximum V. Moreover, the right arm was the dominant arm for all swimmers, with swimmers having higher V maxima during the UWP of the right than the left arm (with the exception of one swimmer that had overall symmetry). These findings implied that the higher roll values on the left side might be associated with the higher V maxima of the right arm. Yanai (2001; 2004) showed that the magnitude of body roll is dependent on internal and external forces applied during a SC. Considering that the higher V maxima during the right arm UWP were possibly associated with higher propulsive forces of this arm (as opposed to the left arm), it is possible that these forces had vectors acting in the vertical and lateral directions. Therefore, it would be reasonable to assume that the larger forces (during the right than the left arm UWP) in the vertical and lateral directions could partially explain the larger shoulder roll values for the left side.

Another possible cause of shoulder roll asymmetries could be the influence of breathing preference. Although the swimmers in the present study were instructed to refrain from breathing while swimming through the pre-calibrated space, it might be possible that asymmetries in kinematic characteristics of breathing cycles could still influence the technique used during non-breathing cycles. For example, it would be expected for swimmers to have larger shoulder roll towards the breathing side during a breathing cycle. Therefore, it would be of interest to examine whether swimmers would maintain that asymmetry during non-breathing cycles, if they would adopt a symmetrical pattern or (while trying to compensate for the breathing cycle asymmetry) even display larger roll values to the non-breathing side.

Even though the present study was not designed to examine the influence of parameters such as those described above, post-test communication with the participants revealed that the group consisted of eight swimmers with right side and two with left side breathing preference, with the remaining swimmer breathing bilaterally. The swimmer who had shoulder roll symmetry had right side breathing preference. Considering the shoulder roll asymmetries and the breathing preferences of the group, there was no clear indication of association between the two. However, the number of swimmers with bilateral breathing and left side breathing preference in the present study was very small and insufficient to lead to any valid conclusions. Further analysis is required to investigate the breathing side influence on the rolling values of freestyle swimmers. A future study could be designed to test differences between three groups (i.e. right and left side breathing preference and bilateral breathing) of a sufficient number of swimmers, who would be tested during non-breathing as well as during right and left side breathing cycles.

5.4 Kinematic parameters of the upper and lower extremity

Methodological limitations could have introduced errors to the measurement of MEF and MKF in existing studies. Moreover, no studies in this area have calculated these parameters for both the left and the right sides. Therefore, one of the purposes of the present study was to calculate accurately the magnitude of MEF and MKF throughout 200 m freestyle and to examine their relationships with V.

5.4.1 Elbow angular motion during the underwater phases

5.4.1.1 Angular patterns and timing of maximum flexion

The analysis of this study showed that swimmers' arms entered the water slightly flexed at the elbow and glided forward (stretching to almost 180°) without applying any propulsion until commencement of the 'catch'. The elbow then started flexing until MEF (minimum elbow joint angle), which was followed by another extension of the elbow until the hand exited the water. One distinct MEF value was recorded for each elbow. It was also shown that freestyle swimmers had MEF during the second half of the UWP of the stroke, when the hand was moving backwards and upwards (elbow behind the shoulder on the horizontal axis). MEF occurred at the same part of the SC as minimum horizontal V of the CM. The latter phenomenon was discussed in section 5.2.3.1.

Even though the timing of MEF did not change significantly throughout the 200 m, faster swimmers attained MEF significantly later than slower swimmers in SC1. It is possible that these differences in the timing of MEF were associated with longer pulling patterns of the faster swimmers for the part between hand entry and MKF.

In other freestyle studies, Payton *et al.* (2002) reported that elbow flexion continuously increased during the insweep phase ('from the instant the hand reached its most lateral to the instant it reached the most medial position'). However, these investigators did not analyse the complete UWP of the stroke due to restrictions in the methodologies used and, therefore, it was not possible to estimate the exact timing of underwater MEF.

5.4.1.2 Magnitude of maximum elbow flexion, changes throughout the test and relationships with performance

The mean minimum elbow angle values (representing MEF) were 98.1 ± 5.8° for the left and 96.8 ± 5.2° for the right elbow. There were low correlations between average horizontal V and MEF for the right and left sides, showing no particular trend between faster and slower swimmers and suggesting no association between performance and the magnitude of MEF. However, swimmers flexed their elbows less in SC1, when V was significantly faster than the other three SCs.

These findings implied that there might be an underlying relationship between the magnitude of MEF and average swimming V, but it was not evident for the comparisons between faster and slower swimmers for each SC due to the small range of velocities. The changes observed across the test suggested that swimmers would tend to swim with a straighter arm in higher velocities. These relationships could be explored by testing swimmers on different event distances or for a range of moderate to maximum velocities. Moreover, to identify the parameters that distinguish between faster and slower swimmers, future studies should focus on other aspects of the underwater motion of the upper extremities, such as: the angular V and the internal/external rotations of the elbow, the orientation of the different segments of the arm, the relative displacements of the shoulder/elbow/wrist joints and the propulsive forces associated with different parts of the UWP of the stroke (and the respective arm positions).

In other studies, Cappaert *et al.* (1995) reported angles of 91.5 ± 4.9° for the elite and 114.3 ± 5.1° for the subelite swimmers participating in men's 100 m freestyle race. The values for the elite swimmers were slightly lower and for the subelite swimmers clearly higher than those calculated in the present study. As discussed in previous sections, differences between the present study and the study by Cappaert *et al.* could be attributed to factors such as: the V and the level of the swimmers tested, the influence of breathing actions (not accounted in the latter study) and the calculation of MEF values for just one elbow.

5.4.1.3 Bilateral asymmetries

The bilateral asymmetries in MEF were 5.0 ± 2.2°, with no consistent side dominance identified between swimmers. Nevertheless, the vast majority of swimmers who had lateral dominance in MEF maintained the side bias throughout the 200 m. It was also shown that large MEF values on the left side were sometimes associated with large MEF values on the right side. Finally, the magnitude of asymmetry in MEF values was not associated with performance.

Despite that the magnitude of bilateral asymmetries not being linked to performance, the analysis of MEF for the left and right sides could still provide important information for swimmers and coaches. For example, it was shown that MEF coincides with V minima. Therefore, if a swimmer has bilateral asymmetries in both the magnitude of MEF and V minima, then the analysis of the left and right side values could be informative with respect to the MEF value that is associated with the higher minimum V value. The latter, together with consideration of other parameters of interest (e.g. body positions that minimise resistive forces for these parts of the

SC), could provide a guidance to swimmers for ways of establishing technique symmetry and, at the same time, improving performance.

5.4.2 Knee angular motion

5.4.2.1 Angular patterns and timing of maximum flexion

This study showed between and within swimmer variation in the kicking patterns employed throughout the test, with two-, four- and six-beat kicking patterns used by swimmers. The angular motions of the knees were sinusoidal in appearance. The results showed that MKF values appeared as many as three times during the SC (depending on the kicking pattern) for each knee. Due to within-swimmer similarities in the magnitude of these values, the timing of appearance of the overall maximum value in a SC varied throughout the test. Finally, the analysis of the timing of appearance of one maximum flexion for each knee showed no significant changes throughout the test.

Qualitative analysis of freestyle swimming technique has also shown that swimmers use two-, four- and six-beat kicking patterns (e.g. Maglischo, 2003). Maglischo (2003) stated that swimmers tend to use the two-beat kicking pattern for distance events, as it presumably requires less energy expenditure, with the vast majority of swimmers using a six-beat pattern for sprint events. The latter could probably explain the change from a six- to a two-beat kicking pattern observed for the two slowest swimmers during the test. Nevertheless, Maglischo also stated that the six-beat kick can not be recommended for every swimmer, as the effectiveness of the kicking actions might be influenced by factors such as: anthropometric characteristics, muscular weakness and joint flexibility. The influence of such parameters on the efficiency of kicking patterns and on swimming performance remains to be investigated.

5.4.2.2 Magnitude of maximum knee flexion, changes throughout the test and relationships with performance

The mean minimum knee angle values (representing MKF) were 133.8 ± 9.2° for the left and 131.2 ± 10.1° for the right knee. There were no significant changes in

MKF throughout the 200 m. Moreover, there was no significant correlation between performance and the magnitude of MKF.

Some authors have reasonably suggested that larger MKF values would be beneficial as they would give the leg a larger ROM to produce propulsive forces (Cappaert *et al.*, 1995). However, this notion was not reflected in the relationships between magnitude of MKF and performance in the present study. Possible explanations could be associated with the position of the leg segments (mainly the thigh and the shank) during the appearance of MKF angles. For example, a low knee position during the upwards movement of the foot (possibly associated with a large angle on the hip joint) would increase the frontal surface area and, therefore, increase water resistance and generate propulsive forces (mainly from the motions of the thigh segment) on the opposite direction than the desired motion. Such forces could cancel out some of the effect of the propulsive actions applied during the downwards movement of the foot. Moreover, a high position of the knee during the upwards movement of the foot could result in the foot coming above the water surface, thus reducing the ROM that the shank is producing propulsive forces. The latter was observed frequently among swimmers in the present study. Another possible cause for the lack of association between magnitude of MKF and performance could be the orientation of the kicking actions during the SC. Excessive hip roll and/or technique deterioration could be associated with application of propulsive kicking forces in directions other than the desired direction of motion. For the above reasons and for the purpose of identifying the factors that influence the propulsive efficiency of the kicking actions, further analysis could explore parameters such as: the angular motion of the hip joint, the vertical displacement of the knee and the ankle joints and the orientation of the kicking actions.

In other studies, Cappaert *et al.* (1995) reported angular ROM of $58.2 \pm 5.9°$ for elite and $49.3 \pm 5.2°$ for subelite swimmers. Assuming that the maximum knee angle for all swimmers was 180°, the reported values represented minimum knee angles of 121.8° for the elite and 130.7° for the subelite group. Another study by the same investigators (1996) reported minimum knee angles of 100.8° for sprint (up to 200 m events) and 139.7° for distance freestyle swimmers (above 200 m events).

Despite some of the reported values being similar to those found in the present study, differences of more than 30° existed in some cases.

The results of both of the above studies suggested that faster swimming velocities were linked to larger values for MKF. However, the present study found no indication of differences in the magnitude of MKF between slower and faster swimmers. The discrepancy between this study and the studies by Cappaert *et al.* (1995; 1996) could be related to factors such as differences in the level of swimmers tested and the smaller range of velocities in the present study. Therefore, it would be of interest to investigate whether any correlation would exist if swimmers are tested in different events (e.g. sprint and distance events) and for a larger range of velocities. Furthermore, future studies could explore the influence of other parameters of the lower extremities on performance, such as: the angular V of the knee and the angular ROM and V of the ankle.

5.4.2.3 Bilateral asymmetries

The mean bilateral asymmetries in MKF were $8.6 \pm 5.5°$, with individual differences as high as 25.6°. Nevertheless, the magnitude of asymmetry in MKF did not seem to be linked to CM horizontal V. There was no consistent side dominance in MKF. However, the vast majority of swimmers who had lateral dominance in MKF maintained the side bias throughout the 200 m. Finally, MKF values for the left and right sides were generally not correlated.

As discussed above, it would be reasonable to assume that larger MKF values would be beneficial by giving the leg a larger ROM to produce propulsive forces. However, given that the magnitude of MKF was not associated with performance, research should investigate other kinematic characteristics of the lower extremities, such as the orientation of the leg actions, the vertical displacement and the angular V of the knee and ankle joints. Consideration of these factors and the magnitude of MKF could be informative with respect to performance improvement. Following that, researchers could explore the bilateral asymmetries and provide guidance to swimmers with regard to the technique changes required to establish symmetry and improve swimming performance.

6. Conclusion

6.1 Summary of the main findings

The main purpose of this thesis was to determine accurately, in three directions, the intracycle variations of the V of the CM throughout a 200 m maximum freestyle swim. Moreover, it also sought to examine if the V maxima/minima and the magnitude of V fluctuations are associated with performance. A second purpose was to determine accurately the magnitude of shoulder and hip roll and maximum elbow and knee flexion, and to assess whether these parameters are associated with average swimming V of the CM. Finally, the bilateral asymmetries in all parameters and the association between the magnitude of asymmetries and performance were investigated. The main findings of this study are summarised below.

- **Intracycle velocity**

- Swimmers decreased average V from SC1 to SC2 and from SC2 to SC3, but had no significant changes in V from SC3 to SC4.
- Intracycle horizontal V had two distinct maxima and minima, with one maximum and one minimum value associated with the UWP of each arm. V maxima occurred during the first half (hand moving backwards and downwards) and V minima during the second half (hand moving backwards and upwards) of the UWP of each arm, while the opposite arm was not contributing to propulsion.
- V maxima occurred at approximately the same time of the SC as shoulder/hip roll maxima, while V minima coincided approximately with MEF.
- Faster swimmers achieved higher average V than slower swimmers mainly by reaching higher V maxima, rather than increasing V minima. However, the ability of faster swimmers to limit the decrease in V improved with each SC.
- Noteworthy fluctuations in V were found in all directions, with the magnitude of fluctuations not linked to performance. Nevertheless, horizontal V fluctuations were positively associated with maximum V in most SCs.

- The fluctuation of horizontal V was greater in SC3 than in SC2 and SC4. This increase was mostly associated with a reduction in minimum V.

- **Shoulder and hip roll**
- Swimmers rolled their shoulders considerably more than their hips.
- Shoulders and hips rolled towards the same direction and reached a maximum at similar times during a SC.
- There were two distinct maxima in shoulder and hip roll, one on each side.
- The timings of roll maxima occurred significantly earlier in SC1 than in SCs 2, 3 and 4.
- Hip roll was significantly less in SC1 (when V was higher) than the other three SCs. There were no differences in shoulder roll across SCs.
- The magnitude of shoulder/hip roll was not associated with performance.

- **Maximum elbow and knee flexion**
- Swimmers had less MEF in SC1 than in the other three SCs. The magnitude of MKF did not change significantly during the test.
- The magnitudes of MEF and MKF were not associated with performance.
- Swimmers used two- to six-beat kicking patterns throughout the test. Differences in kicking patterns existed between and within swimmers.

- **Bilateral asymmetries**
- Noteworthy bilateral asymmetries existed in all kinematic parameters. The magnitude of asymmetries was not associated with performance
- All swimmers had higher V during the right arm UWP and rolled the shoulders more to the left (with one exception in each case showing overall symmetry).

6.2 Practical implications

The analysis of intracycle V variations provided useful information for the balance between propulsive/resistive forces during a SC. Swimming performance can improve if swimmers increase the duration of the most propulsive and decrease the duration of the most resistive periods within a SC. In view of the findings of this study, swimmers could be instructed to extend the length of the period that both arms are under water (after the catch is performed and while both arms contribute to propulsion), as this period is associated with the highest net forces during the SC. This could possibly be achieved by an earlier 'catch' and by swimmers taking full advantage of the horizontal ROM of the hand and pushing backwards until the hand exits the water (early hand exit is a common mistake among swimmers). Moreover, considering that resistance is higher than propulsion before the 'catch', an early 'catch' could possibly lead to an earlier initiation of the propulsive phase of the stroke. To facilitate an early 'catch', swimmers should enter their arms in the water in a way that minimises the resistive forces created in the transition between the above and the below water phases, but also ensure that the arms enter the water in such a position and orientation that the forward glide (where the arm applies no propulsion and the cross sectional area exposed to the flow increases) is minimised.

There was a strong indication that swimmers apply greater forces with the dominant arm and/or possibly adopt such body positions that minimise the resistive forces. It would be reasonable to assume that if a swimmer produces maximum V of equal magnitude during the UWP of the non-dominant arm, then the average V of the SC would increase (providing that the swimmer would be equally effective in minimising the resistive forces during the UWP of the non-dominant arm). Moreover, when fluctuation in horizontal V increased significantly during the test (in SC3), the part of the SC that was mostly affected was the one associated with the V minima of the non-dominant arm. The latter implies that swimmers and coaches should focus on the improvement of effectiveness of the non-dominant arm, in order to establish symmetry in technique and improve performance. Increased propulsive effectiveness of the non-dominant arm could be facilitated by strength-specific dry-land exercises followed by appropriate technique drills. For the swimmers tested in this study, the calculation of bilateral asymmetries in V maxima/minima and MEF can be informative with respect to the MEF value that is associated with the higher minimum V, therefore providing an indication of the appropriate combination of kinematic parameters that could lead to performance improvement.

The present study showed within swimmer variations in the magnitude of fluctuation for a given V. However, swimming with less V fluctuations for a given average V should be expected to be more economical and require less energy expenditure. Thus, for the purposes of reducing the energy demands for a given V and maximising swimming efficiency, researchers and coaches should identify the differences in the kinematic characteristics between SCs of different fluctuations for a given average V. Swimmers could then employ the technique that minimises V fluctuations for a given average V.

The present study showed that an increase in the magnitude of hip roll resulted in smaller differences between shoulder and hip roll, which decrease the frontal surface area and are possibly associated with less water resistance. Moreover, research has shown that large SL values might be good indicators of technique efficiency, while large SR values seem to be associated with high energy cost (e.g. Costill *et al.*, 1985). Therefore, if positions of greater magnitude of hip roll are found to be more effective in terms of minimising resistive forces, swimmers could be instructed to try to achieve such positions perhaps by using the highest possible SL for a given V, rather than increasing the forces applied to non-propulsive directions. However, an increase in SL for a given V would probably be associated with an increase in SC time. Therefore, swimmers should practise maximising the SL for a given V by extending the time of the most propulsive parts of the SC, such as the parts that both arms contribute to propulsion.

Swimmers should seek the appropriate magnitude of MKF that would provide the leg with the optimum ROM to produce propulsive forces. However, swimmers must ensure that the feet do not exit the water during the upwards motion of the shank, as this would increase resistance and reduce the effective ROM for application of propulsive forces. Moreover, when the swimmers bend their knees towards MKF they should place the thighs in such positions that would minimise the resistive forces generated by the increase in the frontal area and the forward motion of that segment. Although further research is required to identify the optimum MKF values for a given V and the associated thigh and shank positions, swimmers and coaches could seek the combinations that produce higher velocities by using surface kicking and swimming drills and assessing the differences in performance.

6.3 Recommendations for future research

The present thesis advanced the knowledge on the biomechanics of freestyle swimming by employing an analysis of intracycle and across-event changes in kinematic parameters during a maximum 200 m swim. In light of the findings and the limitations of this thesis, this section presents directions for future research that would improve further the understanding of swimming technique.

This thesis focused on kinematic aspects of freestyle swimming. In view of the advances in swimming analysis methods, investigators should be encouraged to calculate accurately (in 3D) the biomechanical characteristics of backstroke, butterfly and breaststroke swimming. Moreover, an interdisciplinary approach would allow the examination of interrelationships between biomechanical and physiological variables and could provide a clearer and more complete picture of swimming technique. Furthermore, it is possible that a 200 m maximum freestyle swim might incur different physiological demands when performed in a 50 m than a 25 m pool. Given that differences in physiological parameters might affect stroke kinematics, it would be of interest to investigate possible differences between tests held in a 25 m and a 50 m pool.

There was a lack of association between performance and many of the parameters calculated in this study. This may be related to the small range of velocities for the group of swimmers tested. Therefore, it would be of interest to investigate whether any correlations would exist if swimmers are tested in different events (e.g. sprint and distance events) and for a larger range of velocities.

The magnitude of V fluctuations and the ability of a swimmer to produce high V maxima/minima are associated with the applied propulsive and resistive forces. However, the propulsive and the resistive forces acting during swimming are expected to have a non-linear relationship with V. Nevertheless, only the linear relationships between average V and V fluctuations/maxima/minima were examined in this study. Thus, it would be of interest to explore in future studies whether strong associations between intracycle V changes and performance exist when the V changes are normalised to take into account the non-linear relationship between V and resistive forces. Moreover, other factors that influence the magnitude of resistive forces experienced by swimmers could be explored, such as the cross-sectional area exposed to flow, the V of body segments in the direction of travel and the alignment and shape of body segments.

The analysis of intracycle kinematics of the CM was limited to V patterns. However, acceleration data would be informative with regard to the extent that different phases of the SC are propulsive and could improve further the understanding of swimming technique.

The magnitude of MEF and MKF were not associated with performance. Therefore, for the purpose of identifying the parameters that distinguish between faster and slower swimmers, future studies could focus on other aspects of the underwater motion of the upper and lower extremities, such as: internal/external rotations of the elbow; angular V of the elbow, wrist, knee and ankle; orientation of the segments of the upper and lower extremities; relative displacements of the shoulder/elbow/wrist joints and propulsive/resistive forces associated with different parts of the UWP of the stroke (and the respective segment positions).

This study showed that swimmers decreased the differences between shoulder and hip roll when V decreased, suggesting a tendency to use a more hydrodynamic posture. In addition to the investigation of these relationships for other events and distances, future research could adopt a kinetic approach and examine the extent to which changes in shoulder/hip roll are associated with changes in propulsive and resistive forces and the production of torques about the longitudinal axis. Furthermore, other factors such as the effectiveness of the arms for different rolling positions and the influence of these positions on the orientation and application of kicking forces should also be considered.

Lateral dominance was identified in shoulder roll and V maxima. Future studies could explore the causes of these asymmetries by comparing groups of swimmers according to the handedness (right and left handed) and the breathing preference (breathing bilaterally, left side and right side breathing preference). Moreover upper limb flexibility, strength and coordination measurements could be informative for the purpose of assessing their interrelationships with bilateral asymmetries and swimming performance. Following that, researchers could calculate the bilateral asymmetries and provide guidance to swimmers with regard to the technique changes required to establish symmetry and improve swimming performance.

Another area that was not addressed in this thesis and could be explored in future studies is the separation of distinct parts of the UWP of the stroke and the comparative analysis of the variation in kinematic parameters between these parts. Finally, this study restricted the analysis to non-breathing cycles. However, swimmers breathe frequently during a race (with the exception of some sprint events) and the breathing actions are expected to alter the kinematic characteristics of swimming. Therefore, it would be of interest to explore the differences between breathing and non-breathing cycles and to assess the influence of breathing actions on swimming performance.

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Appendices

Appendix A

Data Tables

Table A.1: Methods used for the calculation of SR, SL and average V in swimming

Studies	Stroke rate			Velocity		Stroke length		
	Method			Method		Method		
	1	2	3	1	2	1	2	3
Psycharakis *et al.*, 2002		√		√			√	
Chatard *et al.*, 2001a, b, c & d			√		√			√
Girold *et al.*, 2001a & b			√		√			√
Chollet and Pelayo, 1999		√	√	√	√	√	√	√
Sidney *et al.*, 1999			√		√			√
Pelayo *et al.*, 1996		√		√				√
Arellano *et al.*, 1994			√		√			√
Keskinen and Komi, 1993		√		√			√	
Chengalur and Brown, 1992			√		√			√
Kennedy *et al.*, 1990			√		√			√
Weiss *et al.*, 1988		√			√			√
Craig *et al.*, 1985		√		√			√	
Pai *et al.*, 1984			√		√			√
Letzelter and Freitag, 1982	Not reported							

Stroke rate: Method 1: The number of stroke cycles realised in the whole distance divided by the time needed to swim the same distance. Method 2: Calculation of the average SR for a number of complete stroke cycles, while swimming in the midsection of the pool. Measurements performed with the use of stopwatches. Method 3: Same procedure to Method 2, with measurements performed with the use of a computer digitising system.
Velocity: Method 1: The whole distance swam divided by the time spent. Method 2: A specific distance swam in the midsection of the pool divided by the time spent for this distance.
Stroke length: Method 1: The whole distance swam divided by the number of stroke cycles measured for that distance. Method 2: The average V divided by the average SR (measured with the use of stopwatches). Method 3: Same procedure to Method 2, with measurements performed with the use of a computer digitising system for data collected during swimming in the midsection of the pool.

APPENDIX B

Participant information sheet

Dear swimmer,

The test in which you are invited to participate is a single 200m freestyle swim at maximum effort. No changes in your normal training routine are required for your participation in this test, which will take place in the St Leonard's Swimming Pool.

Before the test, your height and weight will be measured. Moreover, two pictures (one from the front and one from the side) will be taken simultaneously, to be used for calculation of anthropometric characteristics such as the centre of mass. After that, you will do a warm-up of around 1000m, followed by the 200m freestyle swim. For the purposes of the test, your performance will be recorded with underwater and above water cameras. You will start from inside the water by pushing off the wall, and you will be asked to swim with maximum effort, similar to your normal race pace for that event.

The aim of this research study is analyse the swimming technique. In order to assess the fatigue-related changes in your technique and their influence on performance, parameters such as the following will be calculated: velocity of the centre of mass, stroke rate, distance per stroke, body roll, angle and displacement of the elbows and knees etc. The results of these analyses will become available to you and your coach as soon as they have been completed, while a CD with the recorded views of your performance (from all the different cameras) will be given to you as soon as the test is finished.

Your participation in this research is completely voluntary and if you choose to participate you may withdraw at any time. You understand that you accept to take part in this research in your own responsibility and that the researchers have no liability for anything that may happen during the research procedure.

The researchers will be willing to answer any further questions that you may have. We are truly thankful for your co-operation.

Informed consent form	
	(Delete as appropriate)
1. I have read the Participant Information Sheet	Yes / No
2. I have received enough information about this study	Yes / No
3. I have had the opportunity to ask questions and discuss the research study	Yes / No
4. I understand that I am free to withdraw from the study at any time without giving a reason	Yes / No
5. I do grant permission for the video recordings to be shown to others for educational purposes, for example on the world wide web	Yes / No
6. I agree to take part in this research study	Yes / No
Signature of the participant: (or parent/guardian of participating child) **Name:**	Date:
Signature of the investigator: **Name:**	Date:

Published paper for the calibration frame project

Paper presented at the XIII International Symposium of Biomechanics in Sports, Beijing, China, 22-27 August 2005) and published in the Conference Book of Proceedings.

Reference: Psycharakis S G, Sanders R & Mill F, (2005). A calibration frame for 3D swimming analysis. In, Wang Q (Ed.): *Proceedings of the XVII International Symposium on Biomechanics in Sports.* Beijing, China. Pp.: 901-905.

A CALIBRATION FRAME FOR 3D SWIMMING ANALYSIS

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The purpose of this study was to construct a calibration frame for accurate three- dimensional analysis of swimming and to assess its accuracy and reliability. A 6.75m^3 frame was constructed. The frame was positioned in a 25m pool so that half was above and half below the water surface and recorded with four underwater and two above water synchronised cameras. Direct linear transformation methods were used to estimate marker locations on the frame. Comparison among different numbers of control points showed the set of 20 points to produce the most accurate results. Selection of the most accurate control points improved the accuracy of the measurements even when only 10 control points were used. The frame was found to have high accuracy (mean errors: 3.3mm, 2.6mm and 4.0mm; root mean square errors: 3.9mm, 3.8mm and 4.8mm) and reliability (SD: 0.4mm, 0.5mm and 0.4mm).

KEY WORDS: Biomechanics, underwater, three-dimensional, accuracy, reliability

INTRODUCTION: Most studies of swimming have been limited to two-dimensional (2D) analysis techniques. Errors associated with 2D analysis can be great because swimming is not a planar activity for any of the major strokes. Therefore, a single-camera 2D analysis does not enable accurate quantification of the motion of the whole body. The assumption of bilateral symmetry is also untenable due to asymmetric patterns in the technique (Arellano *et al.*, 2003) and asymmetries in the anthropometric characteristics (Tomkinson *et al.*, 2003).

Therefore, accurate analysis of swimming technique requires three-dimensional (3D) analysis methods. The application of such methods in swimming is complicated due to several factors including the need to digitise body landmarks that move across two media. In addition, filming underwater is problematic and introduces errors additional to those associated with analyses of motion in air (Kwon, 1999).

One of the pre-requisites for accurate quantification of the variables of interest is accurate calibration of the 3D space as part of the process of 3D coordinate reconstruction by the direct linear transformation (DLT) method. Therefore, the purpose of this study was to construct a calibration frame for 3D swimming analysis and to assess the accuracy and reliability of this frame for calculation of points in the space below water.

METHODS: A 3D calibration frame was constructed comprising three parts with the following dimensions: 1.5 m (length) x 1.5 m (height) x 1 m (width). The parts were designed to join to form a rectangular prism of 4.5 m length, 1.5 m height and 1 m width, enabling the calibration of a space of 6.75 m^3 in total. Each side of each part was a 12 mm diameter aluminium tube. This material was selected on the basis of its high flexural stiffness relative to its weight to minimise distortion of the frame during research or storage in a pool environment. Joints were formed by inserting tubes into holes that had been drilled with fine tolerances into solid cubes of aluminium (sides of 51 mm length). Lengths of 2 mm wire were used to triangulate each part of the frame to minimise distortion and adjusted according to the readings of the surveying tools to ensure that the adjoining sides of the frame were orthogonal. The frame was supported on 8 aluminium tubes with circular bases of 64mm diameter attached to the bottom eight joints of the frame. The supporting tubes were adjustable to enable the frame to be positioned with half above and half below the surface of the water. Figure 1 shows an underwater view of the frame.

A total of 92 (46 above and 46 below water) polystyrene spheres, 3 cm in diameter, were drilled through the centre and arbitrary placed on the tubes and wires as control points. The spherical shape ensured that their centres were easily identified from any viewing perspective. The exact co-ordinates of each marker (using a fixed point in the frame as a reference) were measured with the use of surveying techniques and specialist equipment such as square edges, centre finders, spirit levels, and steel rulers. Additional calculations took into account minor alterations in marker locations due to slight bowing of the tubes due to tension. These methods enabled the calculation of the actual values of the coordinates for each marker to an accuracy of ±1mm.

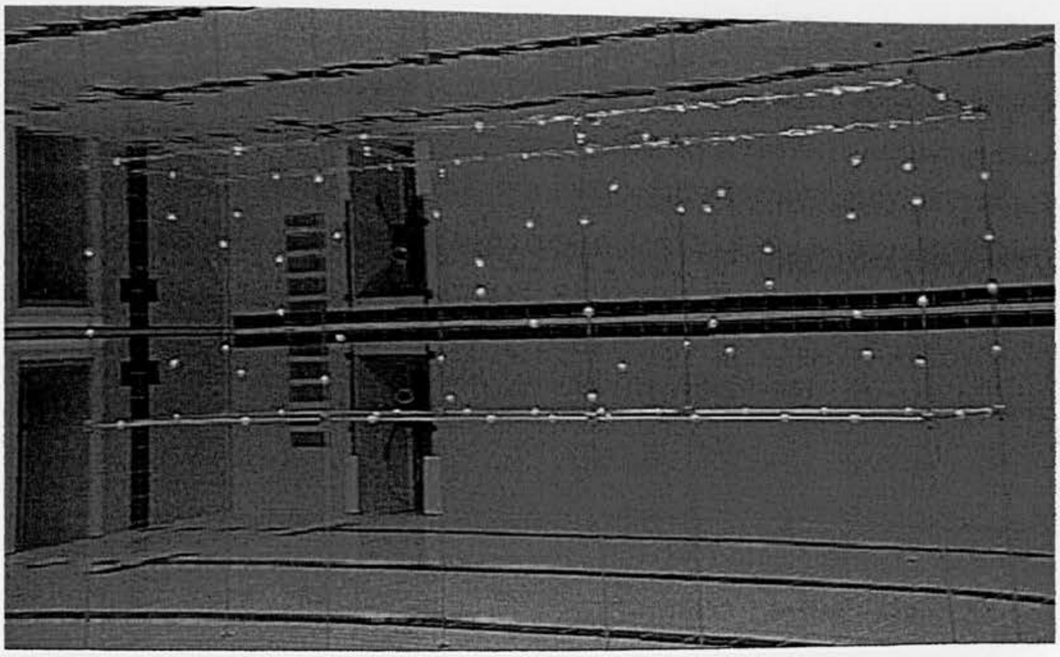

Figure 1: Underwater view of the calibration frame

The calibration frame was placed into a 25 m swimming pool and videoed simultaneously by 4 under and 2 above water synchronised JVC KY32 CCD video cameras. The underwater cameras were approximately 8 m and the above water 12 m away from the centre of the frame. The cameras were at depths varying from 0.5 to 1.5 m below the water surface to avoid errors due to the camera axes being in the same planes as the reference planes of the frame. The angle between the axes of the two above water camera axes was approximately 100°, while the angles between axes of adjacent below water camera axes varied from approximately 75° to 110°. The camera settings were adjusted so that each camera was recording a space 6.5 m long, that is, 1 m each side beyond the frame.

The following procedure was applied to assess the number of control points required to maximise the accuracy of 3D co-ordinate reconstruction for the below water calibration: 10 markers in the calibrated space were digitised over 10 fields for each underwater camera view. Five series of digitising were performed for this set of 10 markers, using 10, 15, 20, 25 and 30 control points respectively. To avoid overestimating accuracy the 10 markers selected for these comparisons were not included in any set of calibration points (Challis & Kerwin, 1992). The 3D coordinates were obtained using the DLT equations based on the data of all four underwater cameras. The differences between the obtained and the known values were calculated for the X, Y, and Z coordinates of each point for each of the 10 video fields. The absolute values of the average differences for each marker were then summed across the 10 markers and divided by 10 to obtain a mean measure of accuracy for each reference axis. In addition, root mean square (RMS) errors were calculated (Bartlett, 1997). This measure represents the error bounds within which 68% of measures would fall and is the combined effect of accuracy and reliability.

To improve accuracy and reduce digitising time for future research, control points that reduced overall accuracy were eliminated. A set of 10 markers was selected and accuracy estimated for 30 markers (independent of the control markers). Mean differences and RMS errors were calculated for the set of 30 markers using the procedures described above.

To obtain an estimate of reliability, one marker (as well as a set of 10 control points) was digitised over 10 fields. The same operator (in order to avoid any inter-operator errors) repeated the procedure 10 times. The reliability measure was the SD across all digitisations of the marker.

Finally, the underwater cameras at the Centre for Aquatics Research and Education are in the water, rather than viewing through external windows. This may reduce errors due to distortion and refraction (Kwon, 1999). However, the cameras are shielded from the swimming public by removable perspex transparent screens. It was of interest to assess whether recording through the perspex screens would increase errors. Therefore, 10 markers in the calibrated space recorded with and without the screens were digitised over 10 fields (with the use of an independent set of 10 control points) and accuracy and reliability assessed in the same manner as described above.

RESULTS AND DISCUSSION:

Table 1 shows the mean difference and the mean RMS errors for the X, Y and Z coordinates of the set of 10 markers, for different numbers of control points. Generally, accuracy increased as the number of control points increased from 10 to 20. A further increase to 25 and 30 points did not improve the accuracy of the measurements.

For the calculations performed following the selection of a set of 10 control points, the mean difference for the set of 30 digitised points was 3.3 mm, 2.6 mm and 4.0 mm, for the X, Y and Z axes respectively. The average RMS error for these points was 3.9 mm, 3.8 mm and 4.8 mm for the X, Y and Z directions respectively, representing 0.1%, 0.2% and 0.5% of the calibrated space. These values were lower than the values found for all the sets of different numbers of control points described above. Thus, by careful selection of control points the accuracy of the measurements can be improved even when only 10 control points are used. Considering the volume of the calibrated space ($6.75m^3$), the errors in this study were similar or lower than those reported in other studies. Payton *et al.* (2002) reported mean errors of 1.5 to 3.1mm for a $1.1m^3$ volume (representing 0.2%, of the calibrated space for each direction). Using a similar volume to this study for a study of the golf swing, Coleman and Rankin (2005) reported RMS errors of 5.1 to 9.8mm (representing 0.4%, 0.5% and 0.3% of the calibrated space, for the X, Y and Z directions respectively).

The reliabilities indicated by repeated digitisations of one marker were ±0.4mm, ±0.5mm and ±0.4 mm, for the X, Y and Z axes respectively. No reference has been made to the reliability of calibration frames used in other swimming studies.

The mean differences and the RMS errors with and without screens are shown in Table 2. These calculations revealed that the screens had only a small effect on the accuracy of the measurements.

Table 1: Mean difference and mean RMS errors for the X, Y and Z co-ordinates of a set of 10 markers, for sets of 10, 15, 20, 25 and 30 control points

Number of control points	Mean difference (mm)			Mean RMS errors (mm)		
	X	Y	Z	X	Y	Z
10	7.6	5.4	6.3	7.8	6.2	6.7
15	6.1	6.0	4.9	6.3	6.9	5.4
20	4.5	5.7	4.7	4.8	6.5	5.2
25	4.3	6.8	5.8	4.7	7.3	6.4
30	5.4	6.4	5.6	5.7	6.9	6.1

Table 2: The mean differences and RMS errors are shown without screens and with screens

Without Screens						With Screens					
Differences (mm)			RMS errors (mm)			Differences (mm)			RMS errors (mm)		
X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
3.6	2.9	5.3	4.1	3.8	6.1	4.2	3.3	5.1	4.6	3.7	6.0

CONCLUSION: The use of 20 control points was shown to provide the most accurate results among sets of various numbers of control points. Nevertheless, a selection of the most accurate markers to serve as control points improved the accuracy of the measurements even with the use of 10 control points. In general, the calibration frame constructed in this study appeared to have good accuracy and reliability relative to others reported in the literature. There was no obvious increase in errors caused by light refraction due to the presence of transparent screens in front of the camera lenses. Based on these results it was concluded that the constructed frame could be used for 3D swimming analysis.

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Construction process of the calibration frame

The 3D calibration frame was constructed comprising three parts with the following dimensions: 1.5 m (length) x 1.5 m (height) x 1 m (width). The parts were designed to join to form a rectangular prism of 4.5 m length, 1.5 m height and 1 m width, enabling the calibration of a space of 6.75 m^3 in total (Figure 3.3, section 3.2.2.1). Each side of each part was a 12 mm diameter aluminium tube. This material was selected on the basis of its high flexural stiffness relative to its weight to minimise distortion of the frame during research or storage in a pool environment. Joints were formed by inserting tubes into holes that had been drilled with fine tolerances into solid cubes of aluminium (sides of 51 mm length) (Figure B.1).

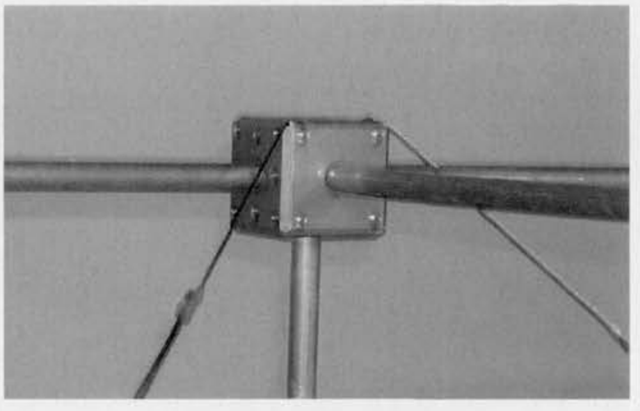

Figure B.1: Aluminium tubes used to form calibration frame joints

To further minimise distortion, lengths of 2 mm wire were used to triangulate each part of the frame, with each of the top four joints of each part connected to the diametrically opposite joint. The wire connecting every pair of joints was attached to a flexible construction made by wire rope grips, wire rope thimbles and turnbuckles (Figure B.2). These wire constructions enabled and facilitated the precise adjustment of the wires at equal lengths. The latter, together with adjustments made with the use of surveying tools, ensured that the adjoining sides of the frame were orthogonal. Once the adjustments had been finalised, the wires were glued at their ends (turnbuckle connections) and the tubes were firmly screwed to the respective joints, to eliminate any internal movement that could alter the geometry of the frame.

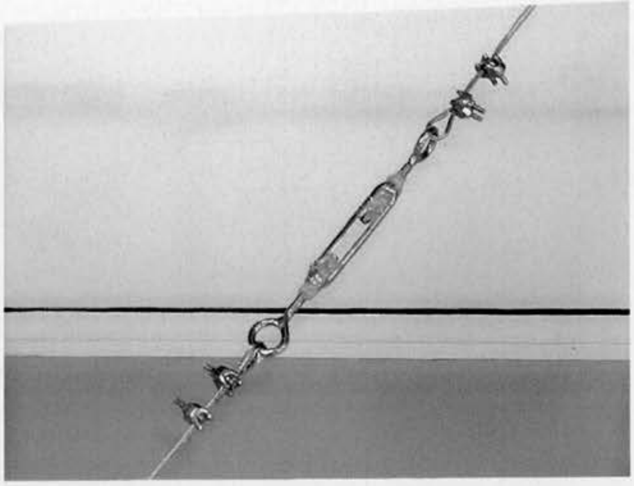

Figure B.2: Wire connection used to triangulate and minimise distortion of the calibration frame

When placed in the pool for calibration purposes, the frame was supported on eight aluminium tubes with circular bases of 64 mm diameter, which were attached to the bottom eight joints of the frame. These supporting tubes were of adjustable lengths, to enable the positioning of half the frame above and half below the water surface. Adjustability was further facilitated by marking the mid-points of all the vertical tubes and aligning these markings with the water surface each time the frame was used for calibration. Figures 3.4 and 3.5 (section 3.2.2.1) show an underwater and an above water view of the frame.

A total of 92 (46 above and 46 below water) polystyrene spheres, 3 cm in diameter, were drilled through the centre and placed in random positions on the tubes and wires to serve as calibration points. The spherical shape ensured that their centres were easily identified from any viewing perspective. For the purpose of marker identification, each joint was named after a letter (from A to I, 16 joints) and each marker was given a code consisting of two letters (those of the adjacent joints) and a number. The number represented the position of a marker in relation to other markers on the same tube/wire, with reference to the first of the two adjacent joints (represented by the first of the two letters in the marker's code). For example, the marker AB1 was the first marker (the one closest to joint A) on the tube connecting joints A and B.

The exact coordinates of each marker (using a fixed point in the frame as a reference) were measured with the use of surveying techniques. For these measurements, specialist equipment (obtained from the School of Engineering and Electronics, Institute of Material and Processes, University of Edinburgh) was used, such as: square edges, centre finders, spirit levels and steel rulers. Additional calculations were made to take into account any slight alterations that could have been caused to the coordinates of the markers from factors such as: bowing of the tubes due to tension; offsets of the markers positions at the tubes/wires and offsets of the joints estimated positions. The methods and equipment used for the aforementioned measurements allowed the calculation of the real values of the coordinates for each marker to an accuracy of ± 1 mm. The values for all markers are shown in Table B.3 (Appendix 2).

Validation process of the calibration frame

To be worthwhile, any coordinate reconstruction technique needs to be accurate and reliable (Challis, 1997). This includes the calibration methods and techniques being used for any image-based motion analysis. For estimation of accuracy and reliability, the calibration frame was placed in the pool and recorded with all six cameras. The calibration frame position and the camera set up and settings were identical to those used for subsequent data collections (as described in sections 3.2.1 and 3.2.2.1).

- **Accuracy and reliability of coordinate reconstruction**

Accuracy is the difference between the true locations of the control points and their predicted values (Challis, 1997). Accuracy in this study was assessed by digitising the calibration frame markers and obtaining the 2D coordinates for each camera view. The 3D coordinates where then calculated for each marker using the Direct Linear Transformation (DLT) method (Abdel-Aziz & Karara, 1971). Accuracy was calculated as the difference between the markers calculated coordinate locations and the known (real) values.

For both the above and below water parts of the frame, accuracy was estimated for all markers that were perfectly visible from all (two and four, respectively) cameras. A set of 10 calibration points on the frame that did not include any of those markers was used to determine the coefficients of the DLT equations, as it has been shown that the use of the same markers for calibration and accuracy assessment overestimates accuracy (Challis & Kerwin, 1992). The markers were digitised over 10 fields for each view and the 3D coordinates were obtained using the DLT equations with the combination of all cameras. Differences between the obtained and the known values were calculated for the X (horizontal), Y (vertical), and Z (lateral) coordinates of each point and for all 10 fields. The absolute values of the average differences for each marker were then summed across all markers and divided by 10 to obtain a mean measure of accuracy for each reference axis. The SD of the differences was also calculated, as it gives a good estimation of precision.

In addition, in line with Challis' (1997) recommendations, the root mean square (RMS) errors were calculated, as RMS errors give a rigorous assessment of reconstruction accuracy. Moreover, this measure represents the error bounds within which 68 % of measures would fall and is the combined effect of accuracy and reliability. The RMS errors were calculated by squaring the errors for the coordinates of all digitised markers and for each of the 10 video frames, and then taking the square root of the average of the squares of the errors.

The accuracy calculations for the above and below calibration points used in this study showed mean errors of 2.6 to 4.5 mm and RMS errors of 3.3 to 5.2 mm, representing 0.1 to 0.5 % of the calibrated space in each direction. Not all swimming studies using 3D calibration frames have reported reconstruction accuracy values. Payton *et al.* (1999a; 1999b; 2002) reported mean errors of 2.0 mm, 1.5 mm and 3.1 mm for the X, Y and Z axis respectively, without however mentioning the RMS errors. The calibrated volume in these studies was 1.06 m^3 (1.30 x 0.88 x 0.93 m), meaning that the corresponding percentage errors (expressed relative to the dimensions of the calibrated volume) were 0.2 % in each dimension. However the latter calculations were performed for the mean reconstruction errors, as opposed to the mean RMS errors used in this study, decreasing therefore the magnitude of the corresponding percentage errors. Despite the low reconstruction errors reported for these studies, Cappaert *et al.* (1995) stated that a small calibrated volume increases the possibility of inaccuracies and larger errors caused by extrapolations beyond the calibrated space. This was confirmed by Challis (1995) who, after comparing a conventional with a multiphase DLT procedure, found that extrapolation beyond the calibrated space produced errors up to three times (or up to 14.5 mm) larger than errors produced when the space was normally calibrated.

In a golf swing study, Coleman and Rankin (2005) used a cubical (1.875 m in each dimension) calibration frame of similar volume (6.59 m^3) to the one for the present study (6.75 m^3). These investigators reported RMS errors of 7.1 mm, 9.8 mm and 5.1 mm for the X, Y and Z axis respectively (representing 0.4 %, 0.5 % and 0.3 % of the calibrated space for the respective directions).

Challis (1995) presented a multiphase calibration procedure that enabled the calibration of a 3.6 m^3 volume with a calibration frame of just 0.6 m^3. The RMS errors for each position of the multiphase calibration ranged from 6.1 to 8.5 mm. A similar multiphase calibration procedure was used in a swimming study (Yanai, 2001), where the 2.4 m^3 calibration frame (1.20 x 2.00 x 1.00 m) was placed at eight successive positions along a test section of 8.4 m length. The investigator reported resultant errors (average errors for the three dimensions) ranging from 8.7 to 17.5 mm for eight digitised points (four above and four below water), but did not calculate the corresponding percentage errors for each dimension.

Considering the magnitude of the calculated mean, RMS and corresponding percentage errors (see section 3.2.2.2), the reconstruction accuracy in the present study was in general similar or better than other studies. In addition, the large volume of the calibrated space (6.75 m^3) minimised the possibility of extrapolation beyond that space, increasing further the accuracy of the measurements. Therefore, the errors in the system reconstruction accuracy in this study were considered to be low and acceptable.

- **Reliability of coordinate reconstruction**

Precision (or reliability) is the repeatability with which a measurement can be made. It has been suggested that the main operator should digitise one or more sequences at least twice to obtain an estimate of precision (Challis, 1997). For reliability assessment of the digitising process (and in addition to the calculation of the SD of the differences, mentioned above), the positions of one underwater marker as well as of a separate set of 10 control points were digitised over 10 video fields. The same operator (to eliminate inter-operator errors and to use the same operator as in the data analysis of this thesis) repeated the procedure 10 times. The SD across all digitisations of the marker was calculated as an indication of reliability.

The reliability measures showed differences of the magnitude of ± 0.4 mm, ± 0.5 mm and ± 0.4 mm, for the X, Y and Z axes respectively. These values were considered very small and any effect on the parameters measured in this study would have been negligible, suggesting high reliability of the calibrated frame. No reference has been made to the digitising reliability of calibration frames used in other swimming studies. In non-swimming studies, Challis (1995) reported a difference of ± 0.8 mm between two sets of measurements for a 0.6 m^3 calibration frame, without however clarifying the axis/axes used for these calculations and the number of digitised and calibration points.

- **Errors due to distortion and refraction**

Kwon (1999) stated that filming underwater is problematic and introduces errors additional to those associated with analyses of motion in air. Kwon added that since a water/glass/air interface is always involved in underwater recordings of swimming, light refraction causes image deformation and, therefore, errors occurring due to this factor should be calculated and reported in all studies involving underwater swimming analysis. The underwater cameras at the Edinburgh University pool were in the water, rather than viewing through external windows, which would be expected to reduce errors due to distortion and refraction. However, the cameras were shielded from the swimming public by removable Perspex transparent screens. It was of interest to assess whether recording through the Perspex screens would increase errors. Therefore, 10 markers in the calibrated space were recorded with and without the screens. These markers were digitised over 10 fields (with the use of an independent set of 10 calibration points) and accuracy was assessed in the same manner as described above.

The mean differences and the RMS errors with and without screens are shown in Table B.1. The accuracy for the two conditions was similar, with the calculated errors ranging from 0.1 to 0.6 mm. Given the reliability calculations mentioned above, the screens did not seem to affect the accuracy of the measurements. Repeated measures ANOVA confirmed that no significant differences existed between the two conditions. Nevertheless, for the purposes of maximising the clarity and visibility of the recorded images, it was decided to remove the screens during each recording session for this study.

The RMS errors caused by light refraction ranged from -0.1 to 0.5 mm, falling within or close to the reliability calculations and indicating that the screens could have had only a negligible effect on the measurements. Light refraction errors have not been reported in the vast majority of swimming studies. Kwon (1999) reported RMS errors in the range of 3.7 to 87.7 mm for a series of different conditions, including alteration of camera-to-interface distance, interface-to-control object distance, camera angle etc. The larger errors observed in Kwon's study could possibly be explained by differences in the methodological procedures, such as the following: 2D DLT method used (as opposed to 3D DLT in this study); cameras positioned in dry rooms behind underwater windows (as opposed to cameras fixed in the water in this study) and theoretical refraction model used to obtain the comparator coordinates of the control points (as opposed to digitising in the present study).

Table B.1: Mean differences and RMS errors calculated with and without screens in front of the underwater cameras

Without Screens						**With Screens**					
Differences (mm)			**RMS errors** (mm)			**Differences** (mm)			**RMS errors** (mm)		
X	**Y**	**Z**	**X**	**Y**	**Z**	**X**	**Y**	**Z**	**X**	**Y**	**Z**
3.6	2.9	5.3	4.1	3.8	6.1	4.2	3.3	5.1	4.6	3.7	6.0

- **Assessment of the number of calibration points used for analysis**

For camera calibration, DLT methods require a minimum of six non-coplanar points in each camera view, with up to 20 points often used in studies (Hamill & Selbie, 2004). For example, Cappaert *et al.* (1995; 1996) used 24 calibration points (12 above and 12 below water) for a 5.6 m^3 calibration frame, while Payton *et al* (1999b; 2002) used 25 points for a 1.1 m^3 calibration frame. Given the lack of information with respect to the number of calibration points required to maximise the accuracy of reconstruction, researchers tend to arbitrary choose the number of calibration points used in studies. Nevertheless, it would be of interest to identify which number of calibration points (between sets of different numbers) would minimise reconstruction errors. For that reason, 10 below water markers in the calibrated space were digitised five times (over 10 fields), using 10, 15, 20, 25 and 30 calibration points respectively. The markers selected for these comparisons were not included in any set of calibration points, to avoid any overestimations in accuracy (as suggested by Challis & Kerwin, 1992). The procedure for accuracy estimation was followed for these comparisons (as described above). Thus, the mean difference, SD and RMS errors were calculated for the coordinates of all 10 markers and for each different set of calibration points.

Table B.2 shows the mean difference and the mean RMS errors for the X, Y and Z coordinates of the set of 10 markers, for different numbers of calibration points. The lowest errors were found for the set of 20 calibration points. However, the mean differences and RMS errors between sets of calibration points were small and not significant ($0.434 \leq p \leq 1.000$).

Table B.2: Mean differences and RMS errors between calculated and real values for the coordinates of a set of 10 markers, digitised with the use of different numbers of calibration points

Number of control points	Mean difference (mm)			Mean RMS errors (mm)		
	X	Y	Z	X	Y	Z
10	7.6	5.4	6.3	7.8	6.2	6.7
15	6.1	6.0	4.9	6.3	6.9	5.4
20	4.5	5.7	4.7	4.8	6.5	5.2
25	4.3	6.8	5.8	4.7	7.3	6.4
30	5.4	6.4	5.6	5.7	6.9	6.1

Psycharakis *et al.* (2005) showed that with selection of the most accurate calibration markers accuracy can be improved even when only 10 points are used. However, the 10 most accurate calibration points used for these preliminary analyses assessed the accuracy of a set of 30 digitised points (as opposed to 10 digitised points used for the comparisons shown in Table B.2) Therefore (taking into account the data shown in Table B.2), it was of interest to assess the differences between the sets of 10, 15, 20 and 25 most accurate points (of the 30 points originally used) on the same set of digitised points and for both above and below water. The comparison showed lower errors (differences ranging from 0.2 to 1.4 mm for all axes) when 20 calibration points were used. Nevertheless, the differences between different sets of control points were not significant ($0.358 \leq p \leq 1.000$). For the purposes of ensuring a big number of calibration points that would be evenly scattered and would cover a considerable part of the volume of the large digitised space without decreasing measurement accuracy, it was decided to use 20 calibration points for the subsequent swimming analyses. The average errors (and RMS errors) for the 20 below water calibration points used in this study were: 2.6 mm (3.3 mm) for the X, 2.4 mm

(3.6 mm) for the Y and 4.5 mm (5.2 mm) for the Z axis. For the 20 above water calibration points the errors were: 3.5 mm (3.9 mm), 3.3 mm (3.8 mm), and 3.8 mm (4.2 mm) for the X, Y and Z axes respectively. The average RMS errors for both the above and below water points represented 0.1%, 0.5% and 0.5% (0.4% for the above water points) of the calibrated space for the X, Y and Z directions respectively.

Data Tables

Table B.3: Calculated coordinates (mm) of the markers of the 3D calibration frame

Marker	X	Y	Z	Marker	X	Y	Z
AB1	-1	295	-5	PK2	1498	501	1008
AB2	0	598	-11	PK3	1505	1201	1009
AB3	4	1098	-15	OL1	2997	198	997
AH1	400	1	1	OL2	3006	1000	1005
AH2	797	0	4	NM1	4511	498	1006
AH3	1197	-3	3	NM2	4507	1303	998
HG1	2002	-1	2	JB1	5	1500	792
HG2	2403	-1	-4	JB2	7	1500	387
HG3	2838	1	-4	IA1	2	-1	600
GF1	3296	-1	-6	IA2	3	0	198
GF2	4099	1	-2	PH1	1503	3	856
FE1	4500	399	1	PH2	1502	7	351
FE2	4499	1201	-4	KC1	1508	1500	655
DE1	3309	1502	-2	KC2	1508	1503	255
DE2	3910	1507	2	OG1	3004	6	594
CD1	1764	1502	5	LD1	3006	1500	692
CD2	2288	1503	-3	NF1	4504	2	398
CD3	2738	1501	-3	ME1	4511	1501	396
BC1	257	1499	-9	AK1	274	240	189
BC2	660	1495	-3	AK2	495	462	335
BC3	1160	1501	1	AK3	1101	1122	734
HC1	1500	356	0	HJ1	1164	307	230
HC2	1505	904	-3	HJ2	865	630	426
HC3	1506	1355	1	HJ3	500	1022	664
GD1	3002	299	-10	IC1	308	278	792
GD2	3004	1105	-10	IC2	849	854	440
IP1	297	2	1002	IC3	1173	1198	231
IP2	594	4	1005	PB1	1039	440	690
IP3	997	4	1005	PB2	596	926	387
PO1	1707	0	1005	PB3	382	1150	248

PO2	2043	-1	1000	HL1	1771	238	187
PO3	2720	0	997	HL2	2316	818	539
ON1	3495	1	997	GK1	2882	74	80
ON2	4296	-1	1001	GK2	2066	952	627
JK1	456	1497	998	PD1	1985	467	675
JK2	907	1494	1002	PD2	2549	1067	304
JK3	1356	1498	1007	OC1	2354	641	567
KL1	1794	1504	1007	OC2	1868	1165	249
KL2	2497	1501	1003	GM1	3445	423	293
KL3	2758	1502	998	GM2	4167	1191	764
LM1	3507	1500	996	FL1	4222	247	191
LM2	4109	1501	996	FL2	3595	922	600
IJ1	-2	504	1002	OE1	3588	574	604
IJ2	-3	848	1000	OE2	4100	1117	273
IJ3	5	1350	997	ND1	4163	309	770
PK1	1495	98	1004	ND2	3534	987	352

Table B.4: Anatomical markers and marker locations for the eZone method

Anatomical Landmark	Side View Marker Location	Front View Marker Location
Vertex	Highest point of head in line with auditory meatus	Midline of head at highest point
C2	Mandible Angle	Centre of chin
C7	At level of C7 but in centre of neck segment	Adam's apple
AC Joint	AC Joint	Same marker as side view
Head of humerus	Head of humerus	On the midline of the arm at same level as side marker
Elbow	Elbow	Elbow
Wrist	Wrist	Wrist
Finger	Tip of longest finger	Same marker as side view
Xiphoid	On the midline of the trunk at same level as front marker	Base of sternum
Pubic	Not required	Applied by the subject
Greater trochanter	Greater trochanter of femur	On the midline of the thigh at same level as side marker
Knee axis	Knee axis	On the midline of the knee at same level as side marker
Ankle axis	Ankle axis	On the midline of the ankle at same level as side marker
Metatarsal phalangeal joint	Metatarsal phalangeal joint	Same marker as side view
Toe	Tip of the longest toe	Same marker as side view

(Adapted from: Deffeyes and Sanders, 2005)

APPENDIX C

Data tables

Table C.1: Individual swimmer data for the average horizontal V of the CM

	Average Horizontal V of the CM (m·sec^{-1})					
Swimmer	**SC1**	**SC2**	**SC3**	**SC4**	**200 m Mean**	**Decrease from SC1-SC4 (% SC1 V)**
1	1.77	1.61	1.60	1.53	1.62	13.63
2	1.70	1.61	1.60	1.55	1.61	9.11
3	1.69	1.56	1.52	1.43	1.55	15.16
4	1.72	1.50	1.47	1.48	1.54	13.55
5	1.69	1.55	1.48	1.45	1.54	14.41
6	1.69	1.54	1.49	1.37	1.52	18.96
7	1.62	1.45	1.42	1.45	1.48	10.57
8	1.62	1.47	1.40	1.45	1.48	10.53
9	1.66	1.47	1.38	1.40	1.48	16.18
10	1.63	1.44	1.40	1.37	1.46	15.85
11	1.53	1.37	1.37	1.37	1.41	10.52
Mean	**1.66**	**1.50**	**1.47**	**1.44**	**1.52**	**13.50**
SD	0.06	0.07	0.08	0.06	0.06	3.03

Table C.2: Individual swimmer data for SR and SL

	Stroke Rate (cycles·min^{-1})					Stroke Length (m·cycle^{-1})				
Swimmer	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**
1	51.73	45.46	47.62	47.62	**48.11**	2.05	2.12	2.01	1.92	**2.03**
2	49.18	43.48	42.86	44.12	**44.91**	2.07	2.22	2.23	2.10	**2.16**
3	41.66	37.97	50.85	38.46	**42.24**	2.43	2.45	1.80	2.23	**2.23**
4	48.39	43.48	44.78	45.46	**45.53**	2.13	2.07	1.97	1.96	**2.03**
5	54.55	50.85	49.18	48.39	**50.74**	1.86	1.82	1.80	1.79	**1.82**
6	46.88	41.09	43.48	40.00	**42.86**	2.16	2.25	2.06	2.05	**2.13**
7	46.88	42.86	44.12	46.15	**45.00**	2.07	2.03	1.93	1.88	**1.98**
8	42.86	40.00	40.00	41.09	**40.99**	2.26	2.20	2.09	2.11	**2.17**
9	55.55	52.63	46.88	46.88	**50.49**	1.79	1.68	1.77	1.78	**1.75**
10	37.97	31.91	30.61	32.97	**33.37**	2.57	2.71	2.74	2.49	**2.63**
11	50.00	41.66	44.12	46.15	**45.48**	1.84	1.96	1.87	1.78	**1.86**
Mean	**49.18**	**43.48**	**42.86**	**44.12**	44.91	**2.11**	**2.14**	**2.02**	**2.01**	2.07
SD	5.37	5.69	5.41	4.74	4.84	0.24	0.28	0.28	0.22	0.24

Table C.3: Individual swimmer data for the horizontal fluctuation of the V of the CM

	Absolute Fluctuation (m·sec^{-1})					% Fluctuation (% of Average V)				
Swimmer	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**
1	0.65	0.64	0.69	0.65	**0.66**	36.62	40.00	43.15	42.86	**40.66**
2	0.88	0.83	0.86	0.67	**0.81**	51.81	51.91	53.79	43.05	**50.14**
3	0.75	0.58	0.64	0.51	**0.62**	44.59	37.20	41.74	35.71	**39.81**
4	0.60	0.57	0.65	0.56	**0.59**	34.84	38.12	43.95	37.66	**38.64**
5	0.65	0.55	0.58	0.61	**0.60**	38.21	35.88	39.02	42.27	**38.85**
6	0.74	0.79	0.96	0.79	**0.82**	43.88	51.36	64.42	57.89	**54.39**
7	0.59	0.43	0.66	0.52	**0.55**	36.31	29.84	46.38	36.00	**37.13**
8	0.51	0.40	0.55	0.48	**0.48**	31.55	27.13	39.48	33.12	**32.82**
9	0.87	0.65	0.68	0.58	**0.70**	52.45	44.52	49.34	41.81	**47.03**
10	0.92	0.74	0.74	0.67	**0.77**	56.52	51.20	52.64	48.71	**52.27**
11	0.52	0.56	0.59	0.53	**0.55**	33.69	41.11	42.95	38.92	**39.17**
Mean	**0.70**	**0.61**	**0.69**	**0.60**	0.65	**41.86**	**40.75**	**46.99**	**41.64**	42.81
SD	0.15	0.14	0.12	0.09	0.11	8.55	8.42	7.59	6.93	6.98

Table C.4: Individual swimmer data for the V maxima during the UWP of the left and right arms

	Maximum V at Right Arm Underwater Phase ($m \cdot sec^{-1}$)					**Maximum V at Left Arm Underwater Phase** ($m \cdot sec^{-1}$)				
Swimmer	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**
1	2.20	1.94	1.99	1.97	**2.02**	2.18	1.97	1.97	1.77	**1.97**
2	2.12	2.05	2.06	1.91	**2.04**	2.00	1.95	1.93	1.85	**1.93**
3	2.10	1.90	1.88	1.73	**1.90**	1.97	1.79	1.77	1.71	**1.81**
4	2.00	1.84	1.84	1.82	**1.88**	2.08	1.79	1.88	1.78	**1.88**
5	2.09	1.88	1.83	1.77	**1.89**	1.81	1.66	1.57	1.54	**1.65**
6	2.11	2.01	2.06	1.83	**2.00**	1.84	1.90	1.84	1.68	**1.82**
7	1.89	1.65	1.73	1.73	**1.75**	1.82	1.57	1.51	1.62	**1.63**
8	1.85	1.67	1.64	1.70	**1.71**	1.85	1.66	1.59	1.63	**1.68**
9	2.15	1.80	1.65	1.75	**1.84**	1.93	1.69	1.58	1.65	**1.71**
10	2.12	1.87	1.78	1.72	**1.87**	1.94	1.78	1.70	1.68	**1.78**
11	1.88	1.70	1.75	1.71	**1.76**	1.57	1.51	1.48	1.52	**1.52**
Mean	**2.05**	**1.85**	**1.84**	**1.78**	**1.88**	**1.91**	**1.75**	**1.71**	**1.68**	**1.76**
SD	0.12	0.13	0.15	0.09	0.12	0.16	0.15	0.18	0.10	0.15

Table C.5: Individual swimmer data for the V minima during the UWP of the left and right arms

	Minimum V at Right Arm Underwater Phase (m·sec^{-1})					**Minimum V at Left Arm Underwater Phase** (m·sec^{-1})				
Swimmer	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**
1	1.59	1.34	1.34	1.35	**1.40**	1.55	1.33	1.30	1.31	**1.37**
2	1.54	1.49	1.48	1.47	**1.49**	1.24	1.22	1.20	1.24	**1.23**
3	1.35	1.32	1.24	1.23	**1.29**	1.45	1.39	1.28	1.22	**1.33**
4	1.49	1.27	1.24	1.27	**1.32**	1.52	1.30	1.35	1.27	**1.36**
5	1.48	1.36	1.30	1.16	**1.33**	1.53	1.33	1.26	1.24	**1.34**
6	1.37	1.22	1.30	1.04	**1.23**	1.49	1.22	1.09	1.10	**1.23**
7	1.54	1.38	1.29	1.26	**1.37**	1.31	1.22	1.08	1.21	**1.20**
8	1.34	1.31	1.25	1.30	**1.30**	1.39	1.27	1.09	1.22	**1.24**
9	1.62	1.40	1.35	1.28	**1.41**	1.28	1.15	0.97	1.16	**1.14**
10	1.44	1.18	1.18	1.20	**1.25**	1.20	1.16	1.05	1.06	**1.12**
11	1.37	1.14	1.22	1.19	**1.23**	1.41	1.20	1.16	1.17	**1.23**
Mean	**1.47**	**1.31**	**1.29**	**1.25**	**1.33**	**1.40**	**1.25**	**1.17**	**1.20**	**1.25**
SD	0.10	0.10	0.08	0.11	0.08	0.12	0.08	0.12	0.07	0.09

Table C.6: Individual swimmer data for the absolute fluctuations of the horizontal V of the CM during the UWP of the left and right arms

	Fluctuation at Right Arm Underwater Phase (m·sec^{-1})					**Fluctuation at Left Arm Underwater Phase** (m·sec^{-1})				
Swimmer	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**
1	0.61	0.60	0.64	0.62	**0.62**	0.63	0.64	0.67	0.46	**0.60**
2	0.58	0.56	0.58	0.44	**0.54**	0.76	0.73	0.73	0.60	**0.71**
3	0.75	0.58	0.64	0.50	**0.62**	0.52	0.40	0.49	0.49	**0.48**
4	0.51	0.57	0.60	0.55	**0.56**	0.56	0.49	0.54	0.51	**0.53**
5	0.61	0.52	0.53	0.61	**0.57**	0.29	0.34	0.32	0.31	**0.31**
6	0.74	0.79	0.75	0.79	**0.77**	0.36	0.67	0.74	0.59	**0.59**
7	0.35	0.26	0.44	0.46	**0.38**	0.51	0.36	0.43	0.42	**0.43**
8	0.51	0.36	0.38	0.40	**0.41**	0.46	0.39	0.51	0.41	**0.44**
9	0.53	0.41	0.30	0.46	**0.43**	0.65	0.54	0.61	0.48	**0.57**
10	0.68	0.68	0.60	0.52	**0.62**	0.74	0.62	0.65	0.62	**0.66**
11	0.51	0.56	0.53	0.52	**0.53**	0.16	0.31	0.32	0.35	**0.28**
Mean	**0.58**	**0.54**	**0.55**	**0.53**	**0.55**	**0.51**	**0.50**	**0.55**	**0.48**	**0.51**
SD	0.12	0.15	0.13	0.11	0.11	0.19	0.15	0.15	0.10	0.13

Table C.7: Individual swimmer data for the percentage fluctuations of the horizontal V of the CM during the UWP of the left and right arms

	% Fluctuation at Right Arm Underwater Phase (% of Average V)					**% Fluctuation at Left Arm Underwater Phase** (% of Average V)				
Swimmer	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**
1	34.49	37.13	40.40	40.52	**38.01**	35.57	39.91	42.15	30.09	**36.97**
2	34.41	35.11	36.06	28.72	**33.63**	44.68	45.36	45.84	38.97	**43.77**
3	44.59	37.20	41.74	34.90	**39.80**	31.04	25.80	32.11	34.31	**30.75**
4	29.84	38.12	41.06	37.18	**36.29**	32.91	32.89	36.49	34.55	**34.15**
5	36.10	33.52	35.97	42.27	**36.87**	16.93	21.83	21.35	21.12	**20.20**
6	43.88	51.36	50.54	57.89	**50.55**	21.03	43.65	49.77	42.78	**38.69**
7	21.80	18.19	31.05	32.07	**25.63**	31.64	24.70	30.34	28.88	**28.96**
8	31.55	24.66	27.57	27.65	**27.95**	28.31	26.33	36.48	28.10	**29.69**
9	32.00	27.71	22.06	33.07	**28.86**	38.90	36.72	43.85	34.63	**38.51**
10	41.79	47.36	43.25	37.89	**42.60**	45.45	43.06	46.72	45.05	**45.07**
11	33.11	41.11	38.63	37.64	**37.49**	10.53	22.82	22.97	25.31	**20.12**
Mean	**34.87**	**35.59**	**37.12**	**37.25**	**36.15**	**30.64**	**33.01**	**37.10**	**33.07**	**33.35**
SD	6.66	9.58	7.91	8.23	7.11	10.98	9.07	9.59	7.30	8.38

Table C.8: Timings for the two V maxima (Max1, Max2) and minima (Min1, Min2)

	SC1	SC2	SC3	SC4	Mean
Min1	0.9 (±8.4)	2.1 (±5.7)	5.0 (±6.5)	7.4 (±5. 5)	**3.8** (±4.6)
Max1	26.6 (±7.7)	32.4 (±6.8)	33.6 (±6.1)	35.3 (±5.0)	**32.0** (±5.8)
Min2	46.8 (±8.4)	49.1 (±7.1)	52.1 (±5.9)	52.5 (±5.2)	**50.1** (±5.8)
Max2	80.8 (±7.3)	81.6 (±4.7)	84.4 (±4.0)	83.8 (±3.3)	**82.7** (±4.4)

Table C.9: Individual swimmer data for the vertical fluctuation of the V of the CM

	Absolute Fluctuation ($m\cdot sec^{-1}$)					**% Fluctuation** (% Average Horizontal V)				
Swimmer	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**
1	0.63	0.56	0.60	0.54	**0.58**	35.61	34.80	37.90	35.43	**35.94**
2	0.71	0.58	0.61	0.61	**0.63**	41.54	35.84	38.01	39.66	**38.76**
3	0.70	0.53	0.50	0.57	**0.58**	41.59	34.17	32.82	39.61	**37.05**
4	0.62	0.59	0.53	0.42	**0.54**	36.19	39.47	36.20	28.55	**35.11**
5	0.43	0.48	0.51	0.53	**0.49**	25.15	30.97	34.34	36.61	**31.77**
6	0.66	0.56	0.51	0.55	**0.57**	38.82	36.54	34.39	40.22	**37.49**
7	0.45	0.38	0.40	0.45	**0.42**	27.54	25.98	28.15	31.11	**28.20**
8	0.60	0.57	0.57	0.53	**0.57**	36.90	38.63	40.88	36.77	**38.30**
9	0.72	0.64	0.57	0.55	**0.62**	43.22	43.46	41.48	39.41	**41.89**
10	0.55	0.61	0.57	0.57	**0.58**	34.05	42.65	41.13	41.30	**39.78**
11	0.47	0.35	0.27	0.31	**0.35**	30.69	25.71	20.02	22.73	**24.79**

Table C.10: Individual swimmer data for the lateral fluctuation of the V of the CM

	Absolute Fluctuation ($m \cdot sec^{-1}$)					% Fluctuation (% Average Horizontal V)				
Swimmer	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**
1	0.53	0.40	0.54	0.47	**0.49**	30.16	24.70	33.87	30.90	**29.91**
2	0.58	0.52	0.58	0.52	**0.55**	34.15	32.38	36.31	33.98	**34.20**
3	0.30	0.40	0.52	0.34	**0.39**	17.98	25.57	34.30	24.01	**25.47**
4	0.31	0.26	0.33	0.38	**0.32**	17.88	17.02	22.35	25.49	**20.68**
5	0.37	0.42	0.33	0.28	**0.35**	21.84	27.06	22.14	19.35	**22.60**
6	0.44	0.51	0.38	0.22	**0.39**	26.03	33.01	25.25	15.95	**25.06**
7	0.37	0.37	0.35	0.27	**0.34**	23.00	25.66	24.63	18.65	**22.98**
8	0.34	0.36	0.32	0.44	**0.36**	21.00	24.18	22.77	30.11	**24.51**
9	0.56	0.42	0.40	0.47	**0.46**	33.94	28.67	28.90	33.95	**31.37**
10	0.51	0.37	0.39	0.43	**0.43**	31.59	25.99	28.08	31.45	**29.28**
11	0.39	0.36	0.20	0.33	**0.32**	25.41	26.38	14.79	24.22	**22.70**

Table C.11: Individual swimmer data for the range of overall shoulder and hip roll

	Shoulder Roll (degrees)					**Hip Roll** (degrees)				
Swim-mer	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**
1	94.6	94.9	101.3	101.2	**98.0**	37.1	52.8	47.7	43.8	**45.4**
2	107.8	106.8	101.4	103.4	**104.9**	43.0	50.4	44.9	49.0	**46.8**
3	102.2	98.0	92.1	96.7	**97.3**	38.7	45.0	37.2	46.4	**40.3**
4	90.6	92.4	99.8	97.8	**95.2**	41.5	42.9	58.4	59.8	**50.6**
5	110.0	107.4	113.4	114.8	**111.4**	38.5	40.2	47.0	52.7	**44.6**
6	96.9	98.5	99.7	101.2	**99.1**	38.7	46.8	40.7	53.5	**44.9**
7	108.9	110.9	118.7	112.8	**112.8**	34.0	38.8	36.8	47.3	**39.2**
8	112.3	119.2	106.0	106.1	**110.9**	50.2	60.4	64.6	56.6	**57.9**
9	115.6	107.3	111.3	106.8	**110.3**	34.9	37.0	66.9	49.9	**47.2**
10	114.7	126.6	124.3	120.6	**121.5**	75.0	84.1	80.6	87.8	**81.9**
11	96.1	92.1	100.4	108.4	**99.3**	44.5	48.0	55.1	57.8	**51.4**
Mean	**104.5**	**104.9**	**106.2**	**106.4**	**105.5**	**43.3**	**49.7**	**52.7**	**54.9**	**50.0**
SD	8.8	11.1	9.6	7.4	8.4	11.5	13.3	13.8	12.0	11.8

Table C.12: Individual swimmer data for the range of shoulder roll to the left and the right sides

	Shoulder Roll Left (degrees)					**Shoulder Roll Right** (degrees)				
Swimmer	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**
1	51.5	51.1	53.0	54.1	**52.4**	43.1	43.8	48.3	47.1	**45.6**
2	53.5	51.8	53.9	50.4	**52.4**	54.3	55.1	47.5	53.0	**52.5**
3	56.6	51.8	50.6	54.4	**53.4**	45.6	46.3	41.5	42.3	**43.9**
4	54.6	56.0	55.3	61.6	**56.9**	35.9	36.4	44.5	36.2	**38.3**
5	56.3	54.0	62.9	61.6	**58.7**	53.8	53.4	50.5	53.2	**52.7**
6	53.4	54.1	53.8	48.2	**52.4**	43.5	44.4	45.9	53.0	**46.7**
7	56.5	58.3	59.6	56.1	**57.6**	52.4	52.6	59.1	56.6	**55.2**
8	62.3	63.3	58.7	60.0	**61.1**	50.0	55.9	47.3	46.1	**49.8**
9	58.9	55.5	57.5	56.7	**57.2**	56.7	51.8	53.7	50.1	**53.1**
10	59.8	68.7	68.4	66.8	**65.9**	54.9	57.9	55.9	53.7	**55.6**
11	48.3	44.9	53.6	60.1	**51.7**	47.8	47.2	46.8	48.3	**47.5**
Mean	**55.6**	**55.4**	**57.0**	**57.3**	**56.3**	**48.9**	**49.5**	**49.2**	**49.1**	**49.2**
SD	4.0	6.4	5.2	5.4	4.5	6.4	6.5	5.2	5.9	5.3

Table C.13: Individual swimmer data of the range of hip roll to the left and the right sides

	Hip Roll Left (degrees)					**Hip Roll Right** (degrees)				
Swimmer	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**
1	17.7	27.0	24.5	22.8	**23.0**	19.4	25.8	23.2	21.0	**22.4**
2	21.8	22.3	23.3	26.2	**23.4**	21.3	28.1	21.6	22.8	**23.4**
3	21.1	23.6	16.4	21.2	**20.6**	17.6	21.4	14.8	25.2	**19.7**
4	27.2	28.1	33.0	34.5	**30.7**	14.3	14.8	25.4	25.3	**19.9**
5	12.2	16.0	19.4	24.2	**17.9**	26.3	24.2	27.7	28.5	**26.7**
6	14.8	16.4	14.3	18.0	**15.9**	23.9	30.4	26.4	35.5	**29.1**
7	16.2	17.5	17.7	19.8	**17.8**	17.8	21.3	19.1	27.4	**21.4**
8	22.9	27.4	28.4	25.0	**25.9**	27.2	33.0	36.2	31.6	**32.0**
9	16.8	17.8	37.6	25.5	**24.4**	18.1	19.2	29.3	24.3	**22.7**
10	38.8	44.9	43.6	47.5	**43.7**	36.2	39.2	37.0	40.3	**38.2**
11	20.4	20.7	26.3	28.8	**24.0**	24.2	27.3	28.8	29.0	**27.3**
Mean	**20.9**	**23.8**	**25.9**	**26.7**	**24.3**	**22.4**	**25.9**	**26.3**	**28.3**	**25.7**
SD	7.3	8.3	9.2	8.2	7.7	6.1	6.8	6.7	5.7	5.7

Table C.14: Individual swimmer data for the timings of the first shoulder (SR-Max1) and hip roll (HR-Max1) maxima

	SR-Max1 (% of SC time)					HR-Max1 (% of SC time)				
Swimmer	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**
1	33.3	30.2	33.3	40.4	**34.3**	16.2	17.2	18.2	19.8	**17.8**
2	18.2	21.2	22.2	26.3	**22.0**	31.3	32.3	36.4	33.3	**33.3**
3	22.2	26.3	28.3	27.3	**26.0**	25.3	27.3	21.2	28.3	**25.5**
4	30.3	30.3	30.3	31.3	**30.6**	33.3	37.4	35.4	33.3	**34.8**
5	34.3	40.4	40.4	40.4	**38.9**	20.2	23.2	24.2	23.2	**22.7**
6	34.3	39.4	33.3	38.4	**36.4**	37.6	43.4	43.4	43.4	**42.0**
7	33.3	35.4	40.4	40.4	**37.4**	18.2	22.2	25.3	24.2	**22.5**
8	20.2	24.2	29.3	26.3	**25.0**	16.2	20.2	26.3	23.2	**21.5**
9	20.2	26.3	26.3	27.3	**25.0**	18.2	29.3	27.3	28.3	**25.8**
10	22.2	32.3	38.4	38.4	**32.8**	25.3	39.4	40.4	45.5	**37.6**
11	23.2	34.3	34.3	36.4	**32.1**	17.2	23.2	25.3	25.3	**22.7**
Mean	**26.5**	**30.9**	**32.4**	**33.9**	**30.9**	**23.5**	**28.6**	**29.4**	**29.8**	**27.8**
SD	6.5	6.1	5.8	6.2	5.7	7.6	8.5	8.2	8.4	7.8

Table C.15: Individual swimmer data for the timings of the second shoulder (SR-Max2) and hip roll maxima (HR-Max2)

	SR-Max2 (% of SC time)					**HR-Max2** (% of SC time)				
Swimmer	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**
1	81.8	83.8	94.9	89.9	**87.6**	72.7	74.7	74.7	74.7	**74.2**
2	77.8	79.8	83.8	76.8	**79.5**	84.8	82.8	90.9	86.9	**86.4**
3	85.9	91.9	91.9	92.9	**90.6**	72.7	72.7	94.9	76.8	**79.3**
4	83.8	84.8	84.8	84.8	**84.6**	78.8	80.8	81.8	82.8	**81.1**
5	86.9	91.9	91.9	89.9	**90.1**	95.1	99.0	96.0	96.0	**96.5**
6	85.9	85.9	83.8	84.8	**85.1**	90.9	92.9	90.9	91.9	**91.7**
7	84.8	86.9	88.9	89.9	**87.6**	70.7	74.7	76.8	74.7	**74.2**
8	67.7	72.7	74.7	73.7	**72.2**	73.7	74.7	77.8	74.7	**75.2**
9	72.7	76.8	81.8	78.8	**77.5**	70.7	76.8	77.8	82.8	**77.0**
10	70.7	83.8	88.9	86.9	**82.6**	74.7	88.9	91.9	89.9	**86.4**
11	81.8	88.9	83.8	84.8	**84.8**	69.7	71.7	76.8	77.8	**74.0**
Mean	**80.0**	**84.3**	**86.3**	**84.8**	**83.9**	**77.7**	**80.9**	**84.6**	**82.6**	**81.4**
SD	6.8	6.0	5.7	6.1	5.6	8.7	9.1	8.3	7.6	7.8

Table C.16: Individual swimmer data for the minimum angle (maximum flexion) of the left and right elbows during the UWP of the stroke

	Left Elbow Minimum Angle (degrees)					**Right Elbow Minimum Angle** (degrees)				
Swimmer	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**
1	107.4	108.6	105.3	106.1	**106.9**	105.2	100.0	88.6	101.3	**98.8**
2	97.4	89.3	94.9	95.8	**94.3**	92.5	98.3	97.5	97.6	**96.5**
3	111.1	103.1	92.5	102.3	**102.2**	101.3	94.5	89.4	98.2	**95.8**
4	96.5	87.8	90.4	91.9	**91.6**	103.7	100.9	98.7	97.2	**100.1**
5	104.6	95.3	97.0	95.9	**98.2**	99.1	101.5	98.1	95.6	**98.6**
6	90.5	93.5	93.0	92.8	**92.5**	89.8	91.9	82.9	80.4	**86.2**
7	115.8	107.8	102.1	103.9	**107.4**	107.8	100.1	101.0	98.7	**101.9**
8	105.8	98.1	91.1	94.5	**97.4**	105.0	96.1	100.8	99.4	**100.3**
9	94.2	91.0	87.0	90.7	**90.7**	92.5	88.2	87.7	90.1	**89.6**
10	100.3	98.1	94.3	95.3	**97.0**	98.3	96.0	93.8	89.4	**94.4**
11	104.8	105.3	98.9	95.6	**101.1**	103.5	102.2	104.6	102.0	**103.1**
Mean	**102.6**	**98.0**	**95.1**	**96.8**	**98.1**	**99.9**	**97.2**	**94.8**	**95.4**	**96.8**
SD	7.6	7.4	5.4	5.1	5.8	6.0	4.4	6.8	6.4	5.2

Table C.17: Individual swimmer data for the timing of the two MEF angles

	Maximum Elbow Flexion 1 (% of SC time)					**Maximum Elbow Flexion 2 (% of SC time)**				
Swim-mer	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**
1	5.9	7.9	8.9	7.9	**7.7**	55.4	56.4	58.4	57.4	**56.9**
2	1.0	1.0	2.0	1.0	**1.2**	51.5	55.4	58.4	57.4	**55.7**
3	1.0	2.0	8.9	6.9	**4.7**	53.5	52.5	56.4	56.4	**54.7**
4	10.9	10.9	11.9	12.9	**11.6**	61.4	62.4	60.4	60.4	**61.1**
5	2.0	5.0	5.0	5.0	**4.2**	48.5	48.5	47.5	48.5	**48.3**
6	1.0	12.9	7.9	10.9	**8.2**	58.4	63.4	61.4	63.4	**61.6**
7	-3.0	-4.0	1.0	-2.0	**-2.0**	48.5	47.5	54.5	53.5	**51.0**
8	1.0	1.0	2.0	4.0	**2.0**	44.6	47.5	52.5	51.5	**49.0**
9	-7.9	-4.0	-3.0	-4.0	**-4.7**	49.5	51.5	54.5	53.5	**52.2**
10	1.0	9.9	15.8	13.9	**10.1**	47.5	61.4	67.3	65.3	**60.4**
11	-5.9	-2.0	-8.9	-6.9	**-5.9**	42.6	45.5	41.6	41.6	**42.8**
Mean	**0.6**	**3.7**	**4.7**	**4.5**	3.4	**51.0**	**53.8**	**55.7**	**55.4**	54.0
SD	5.1	6.0	7.0	6.9	5.9	5.7	6.4	7.0	6.8	6.0

Note: Negative values correspond to modified SC percentage values (negative value = real value – 100 %), which were transformed to give a better indication of mean and SD for the group.

Table C.18: Individual swimmer data for the minimum angle (maximum flexion) of the left and right knees

	Left Knee Minimum Angle (degrees)					**Right Knee Minimum Angle** (degrees)				
Swimmer	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**
1	127.0	129.9	133.0	137.9	**131.9**	129.4	133.4	133.2	142.6	**134.6**
2	137.2	140.8	127.9	139.3	**136.3**	130.6	134.3	113.1	131.5	**127.4**
3	126.1	139.1	131.7	131.0	**132.0**	113.8	116.7	120.5	121.0	**118.0**
4	142.2	133.5	148.0	153.4	**144.3**	151.3	147.8	149.3	151.7	**150.0**
5	117.6	113.7	113.6	118.5	**115.9**	116.5	120.0	116.9	118.4	**118.0**
6	127.6	128.7	135.2	135.3	**131.7**	132.0	138.4	141.6	140.2	**138.1**
7	118.2	118.3	120.1	118.1	**118.7**	127.9	127.1	129.8	130.9	**129.0**
8	134.2	139.6	140.3	139.1	**138.3**	127.5	134.2	133.5	134.2	**132.3**
9	142.4	143.6	139.2	144.2	**142.4**	116.8	122.7	121.1	120.9	**120.4**
10	146.0	137.9	141.5	139.0	**141.1**	137.2	134.1	131.9	129.2	**133.1**
11	139.7	135.6	139.2	141.0	**138.9**	132.9	134.6	150.1	150.6	**142.0**
Mean	**132.6**	**132.8**	**133.6**	**136.1**	**133.8**	**128.7**	**131.2**	**131.0**	**133.7**	**131.2**
SD	9.9	9.5	10.0	10.4	9.2	10.6	8.9	12.5	11.5	10.1

Table C.19: Individual swimmer data for the timing of two MKF angles

	Maximum Left Knee Flexion (% of SC time)					**Maximum Right Knee Flexion (% of SC time)**				
Swim-mer	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**	**SC1**	**SC2**	**SC3**	**SC4**	**Mean**
1	19.8	20.8	20.8	21.8	**20.8**	33.7	34.7	35.6	36.6	**35.1**
2	68.3	69.3	73.3	73.3	**71.0**	18.8	22.8	23.8	24.8	**22.5**
3	38.6	41.6	46.5	41.6	**42.1**	54.5	57.4	66.3	58.4	**59.2**
4	14.9	15.8	15.8	16.8	**15.8**	99.0	100.0	100.0	100.0	**99.8**
5	69.3	70.3	71.3	71.3	**70.5**	97.0	100.0	100.0	100.0	**99.3**
6	60.4	62.4	62.4	63.4	**62.1**	74.3	77.2	76.2	77.2	**76.2**
7	50.5	52.5	55.4	53.5	**53.0**	31.7	34.7	36.6	33.7	**34.2**
8	83.2	86.1	89.1	88.1	**86.6**	1.0	5.9	8.9	7.9	**5.9**
9	86.1	95.0	100.0	94.1	**93.8**	2.0	7.9	10.9	10.9	**7.9**
10	72.3	86.1	92.1	89.1	**84.9**	23.8	36.6	46.5	44.6	**37.9**
11	1.0	4.0	2.0	2.0	**2.2**	50.5	53.5	49.5	50.5	**51.0**
Mean	**51.3**	**54.9**	**57.2**	**55.9**	**54.8**	**44.2**	**48.3**	**50.4**	**49.5**	**48.1**
SD	29.0	30.9	32.8	31.6	31.0	34.4	33.1	32.0	32.0	32.8

APPENDIX D

Data tables

Table D.1: Duration of UWP and recovery phase of each arm during a SC

	UWP Duration (% of SC time)				Ratio of UWP/Recovery Duration (% of SC time)			
	SC1	**SC2**	**SC3**	**SC4**	**SC1**	**SC2**	**SC3**	**SC4**
Left Arm	72.3	75.3 (0.050)*	75.9 (0.061)	76.4 (0.002)*	2.7	3.1 (0.075)	3.2 (0.035)*	3.3 (0.001)*
Right Arm	72.5	76.1 (0.137)	76.0 (0.479)	77.1 (0.115)	2.7	3.2 (0.327)	3.2 (0.732)	3.4 (0.178)

The p values shown in the parentheses represent significance levels between SC1 and each one of the other three SCs. There were no significant differences between SC2, SC3 and SC4 (0.305 ≤ p ≤ 1.000)
*: significant at p<.05