ADVANCING SWIMMING SCIENCE WITH CARE

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Abstract: This paper provides an overview of how the research team at The Centre for Aquatics Research and Education is adding to knowledge in swimming science to assist swimmers and swimming coaches. Topics covered include improving the glide in starts and turns, body roll in front crawl, technique differences between sprint and distance front crawl swimmers at sprint and distance pace, and rhythm in front crawl swimming.

Key Words: body roll, front crawl, passive drag, rhythms, swimming

Introduction: The Centre for Aquatics Research and Education (CARE) was established in 2001 with a mandate to conduct applied research in aquatic activities including swimming and hydrotherapy. This presentation focuses on recent findings in swimming and includes work from three recent graduates from the doctoral programme. Roozbeh Naemi has developed a new method of quantifying the passive drag of swimmers and, as a postdoctoral fellow during the past year has developed 'coach-friendly' software to assist coaches and swimmers to improve their glide performance in starts and turns. Using three-dimensional analysis techniques Stelios Psycharakis has shed new light on the characteristics of body roll in front crawl swimming. While there is some knowledge about how swimming technique differs between swimmers swimming at sprint and distance pace not much is known about whether specialists in sprint swimming differ in technique from distance swimmers when both groups are swimming at race pace over the same distances. In addressing this issue Carla McCabe has uncovered some very interesting as well as some surprising findings. The presentation concludes with a discussion of recent findings with respect to the rhythms and 'body waves' that underpin coordination in skilled front crawl swimming.

Improving Glide Performance in Starts and Turns: Performance in starts and turns is a major contributor to success in swimming and is influenced greatly by the glide performance. It has been established that the glide time after starts and turns corresponds to 10 to 25 percent of total swim time (Chatard et al., 1990). Glide performance depends on the initial velocity of a glide as well as on the glide efficiency, defined as the ability of a body to maintain its velocity and to avoid deceleration (Naemi and Sanders, 2008b).

The initial velocity of a glide is related to the preceding action, and is affected by propulsive force development during pre-glide actions such as pushing off the wall in turns. Increasing the initial

velocity of a glide by increasing propulsive force during the pre-glide phase can improve the glide performance. However, it does so with a metabolic cost and is limited by the athlete's strength. In contrast, maximising glide efficiency (minimising resistance and/or maximising inertia) improves performance without increase in the metabolic cost. A 20% increase in glide efficiency during passive glides achieved by adopting a 'streamlined' posture leads to a 7% increase in the average speed. Depending on the race distance, in which the number of turns varies, this can yield a 0.5 - 3% improvement in the race performance. Such an improvement can change a swimmer's result from being eliminated prior to the finals to being a medallist. Improving glide efficiency enables the swimmer to increase time in the passive glide phase after starts and turns, thereby increasing the period of recovery and reducing the period of active swimming. Thus the knowledge of the factors contributing to glide efficiency and the ways to quantify it are of utmost importance.

The methods used in previous studies (Sharp and Costill, 1989; Starling et al., 1995) do not allow quantification of the glide efficiency at different velocities and do not relate the glide efficiency to the hydrodynamic characteristics of a body. The Hydro-Kinematic Method (HKM) (Naemi and Sanders, 2008b) accounts for the inertial and resistive characteristics of the gliding body. A mathematical function, based on the equation of motion of the gliding body, is fitted to the kinematic position-time data of a swimmer performing a rectilinear glide. From the fitted function a glide factor that represents the ratio of inertia to the resistive factor is deduced that is a measure of the glide efficiency.

The HKM requires only a single underwater camera positioned perpendicular to the swimmer's glide plane and two-dimensional digitising software. This method has advanced the capability of measuring glide efficiency and has been shown to be accurate and reliable enough to detect small differences in glide efficiency. Figure 1 provides samples of the output of the model together with indications of the goodness of fit and its ability to detect differences in gliding ability between subjects and between trials within subjects.
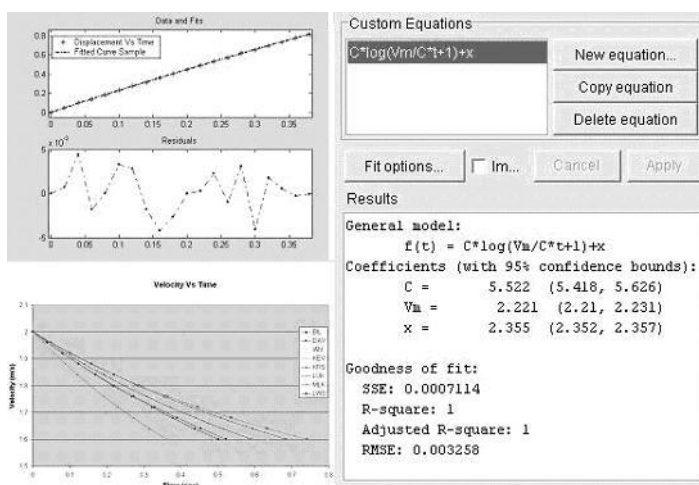
Figure 1. Sample output of the of the HKM. From top left clockwise, raw displacement data and the corresponding fit together with the plot of the residuals; the mathematical model and the quantified parameters obtained for each trial; and the reconstructed velocity Vs time for the subjects.

The development of the HKM provides an opportunity, for the first time, to 'fine tune' swimmers' glide efficiency by adopting the most streamlined position. Many swimmers adopt inappropriate postures during glides. Flow separation, resulting from an excessive angle of attack, increases the 'pressure drag', the main source of drag during an underwater glide. Adopting a body alignment with a minimum angle of attack and maintaining an appropriate posture with suitable joint angles minimises the pressure drag by reducing the area exposed to the flow as well as the flow separation associated with water moving over 'non-streamlined' body contours. Special attention needs to be paid to the neck, hip and knee angles which were found to be significantly correlated to the passive drag and hence the glide efficiency (Naemi, 2007).

It has been established that maintaining a passive streamlined posture at higher velocities than a critical value is more beneficial than an active propulsive movement (Sanders and Byatt-Smith, 2001). This is due to the fact that in these conditions the net decelerating force (the difference between the active drag and the propulsive force) is greater than the passive drag for a gliding position (Lyttle, et al., 2000). This has important implications as a swimmer can lose speed unnecessarily if the passive glide is finished prior to or continued beyond an optimum speed. In these cases, additional energy and time is required to regain the optimal velocity. Thus, it is beneficial to predict the speed at which a swimmer with a particular glide efficiency and post-glide velocity characteristics should commence the propulsive actions (Sanders and Byatt-Smith, 2001). This not only improves performance in the starts and turns but also avoids losing energy unnecessarily, improving performance in the mid-pool phases. Thus it is highly desirable to predict how performance may be optimised by initiating the post-glide phase at the best time. This means that an accurate record of instantaneous velocity during the glide is required in actual un-tethered glides. It is possible to determine the instantaneous velocity of a body during the whole period of a glide by video analyses. However, due to variations in the velocity as a result of instabilities in flow (Howe et al., 2001; Wang et al., 2003) that cannot be distinguished from noise, the determined instantaneous velocity data may not be valid for comparison (Klauck and Daniel, 1976; Naemi and Sanders, 2004). The HKM overcomes that problem by fitting a mathematical function to the raw displacement data enabling precise reconstruction of the velocity variations of the body during a glide (Fig.1). By knowing how the glide efficiency of a swimmer changes across velocities, it is now possible to determine how fast they decelerate during a glide. This information is particularly important in predicting the exact timing for initiating the post-glide action for a particular swimmer with a distinct glide efficiency and post-glide performance. For example for each swimmer the glide should end when the velocity reaches the velocity which can be sustained by the post-glide actions.

Based on the applications of the Hydro-kinematic method (Naemi and Sanders, 2008b) 'user friendly' software named "GlideCoach" has been developed (Naemi et al., 2008) for coaches to provide immediate feedback to swimmers to optimise glide efficiency and time of initiating post-glide actions in starts and turns. The output includes a video replay, graphs, and tabulated results in an aesthetic and

effective display. The 'GlideCoach' software enables coaches to 'fine tune' swimmers' streamlining posture as well as to optimise timing of initiating post-glide actions.

Recent Findings from Three-Dimensional Analysis of Body Roll: It has been suggested that body roll, the rolling action of the trunk around its longitudinal axis, has important functions in front crawl swimming. Such functions include: making the recovery of the arm easier and permitting a shorter radius of rotation of the recovery arm; placing the strongest part of the arm pull more directly under the midline of the body; facilitating the breathing action and; reducing the risk of developing shoulder injuries (Counsilman, 1968; Richardson et al., 1980; Ciullo and Stevens, 1989).

Computer simulation studies have indicated that body roll assists in the development of propulsive forces and, therefore, the improvement of swimming performance (e.g. Hay et al., 1993; Payton et al., 1997). In most empirical studies body roll was measured for the whole trunk by mounting a balsa wood fin on a curved aluminium base and strapping it on the back of each swimmer. Body roll was then defined as the angle between the rear end of the fin and the vertical, and was measured with the use of two-dimensional analysis. Some interesting findings were reported in these studies. For example, it was shown that swimmers roll more during breathing than non-breathing cycles (Payton et al., 1999; Castro et al., 2003), and that they roll less to the non-breathing than the breathing side. Also, body roll was found to decrease with increasing swimming speed (Castro et al., 2003; Yanai, 2003). Nevertheless, there has been evidence that the assumption that the whole trunk rolls as a rigid segment might not be tenable, because the shoulders and hips might roll to different extents and in some cases with different phase (Cappaert et al., 1995; Yanai, 2003).

In an attempt to improve our knowledge of body roll and its possible links to swimming performance, Psycharakis et al. (2007) used a 6-camera system and three-dimensional analysis methods to calculate separately the rolling actions of the shoulders and hips in freestyle swimming. It was indicated that swimmers were rolling their shoulders significantly more than the hips. Moreover, faster swimmers were found to have less shoulder roll than slower swimmers, while no similar trend was identified for hip roll. Figure 2 shows the roll-time profiles of the shoulders and the hips for one of the swimmers tested. The profiles were clearly very different in terms of the magnitude of SR and HR.
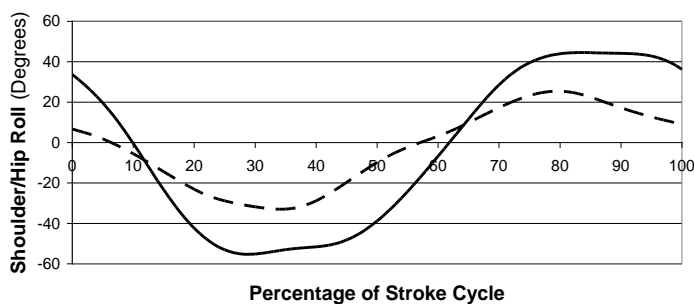
Figure 2: Patterns of shoulder (continuous line) and hip roll (dashed line) for a freestyle swimmer. Positive and negative roll values represent roll to the right and left side, respectively. (Adapted from Psycharakis et al., 2007).

Further to the above, Psycharakis (2006) examined the bilateral asymmetries in shoulder/hip roll, as well as the timing differences for the peak shoulder/hip roll at each side. Eleven national and international level swimmers performed a maximum 200m freestyle swim and four stroke cycles were analysed (one for each 50m). Left side dominance was identified in shoulder roll, while no similar pattern was found for hip roll. Given that all the swimmers tested were right-handed, Psycharakis suggested that factors related to handedness might affect the roll symmetry in freestyle swimming. Finally, despite the inter-individual differences in the timings between shoulder and hip roll peaks in each side, there was no consistent pattern to suggest that the swimmers' shoulders lead the hips or vice-versa. The results of the three-dimensional analyses indicated that shoulder and hip roll should be calculated separately in freestyle swimming.

Do Sprint and Distance Front Crawl Swimmers Differ when Swimming at the Same Pace? Many authors have proposed that sprint and distance front crawl swimmers differ in their stroke characteristics. However, there has been a paucity of three-dimensional quantitative data to support these assumptions.

Some research has indicated that sprint and distance swimmers differ in terms of the magnitude of stroke depth (Cappaert, 1998), stroke width (Colwin, 2002), elbow angle (Wilke, 1992; Cappaert, 1998; Voronstov and Rumyantsev, 2000) and the foot range of motion (Cappaert, 1998). However, in the recent study by McCabe (2007) sprint and distance swimmers did not differ with respect to the aforementioned variables when both swim at race pace over the same distance. Thus, these findings challenge current views with regard to front crawl sprint and distance swimmers.

McCabe did find some differences with respect to other variables. Sprint and distance swimmers are different with respect to the duration of the pull (Figure 3) and push phases ($p<0.05$) (Figure 4). The shorter duration of these phases by the sprint swimmers was linked to a faster horizontal velocity and vertical acceleration of the hand by the latter group within the pull and push phases.

Sprint and distance swimmers had a different sequencing pattern of the shoulder and hip segments - a characteristic not previously investigated. When sprinting, both sprint and distance swimmers rotated the hips prior to the shoulders. The sprint group showed this sequencing pattern distinctively throughout the stroke cycle, whereas was less pronounced with respect to the distance group.

This altered sequencing of the shoulders and hips between groups when sprinting may also explain the differences found between groups in terms of maximum shoulder roll (both sides) with the sprint swimmers obtaining maximum shoulder roll later in the stroke cycle than the distance swimmers when sprinting (Figure 5), perhaps due to a greater time delay between the shoulder and hip segments rotating.
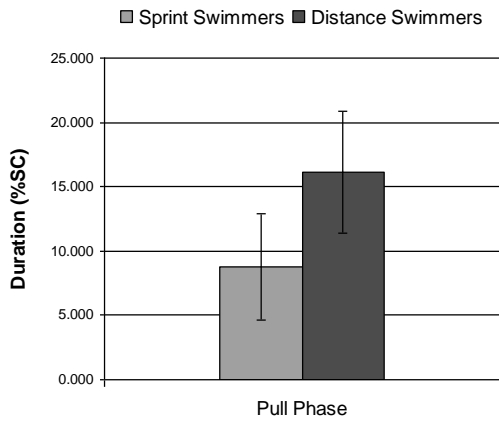
Figure 3: Shorter duration of the pull phase by the sprinters than the distance swimmers when sprinting.
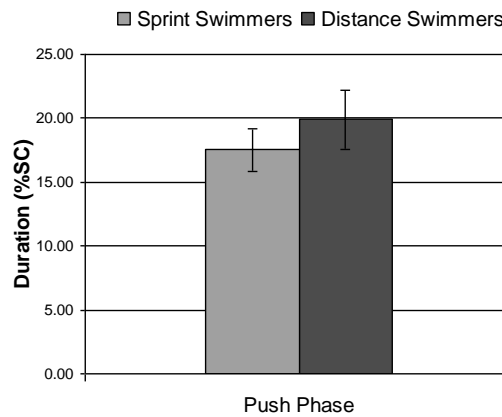
Figure 4: Shorter duration of the push phase by the sprinters than the distance swimmers when sprinting.
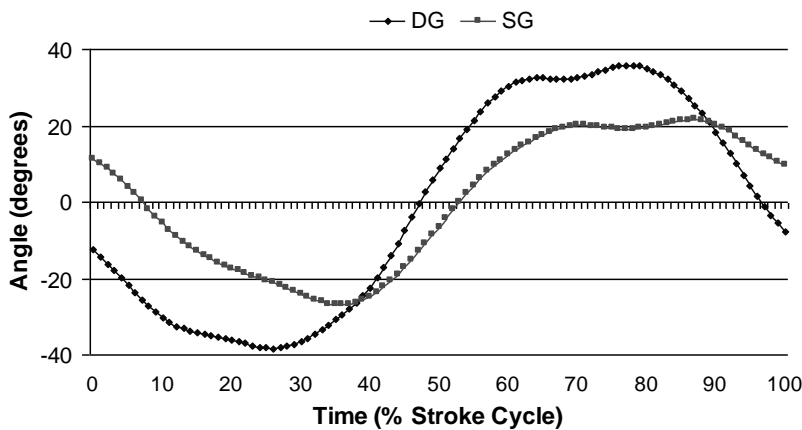

Figure 5: Mean shoulder roll angle for distance and sprint groups. The difference in time of attainment of maximum roll to each side is evident.

When distance swimming, the distance group rolled the shoulders in advance of the hips, whereas the sprint group rolled the shoulders and hips simultaneously. There was some evidence that the different sequencing order of the shoulders and hips between the groups was related to the range of motion of the kick.

Irrespective of the distance specialisation, all swimmers changed a broad range of kinematic and kinetic variables between sprint and distance pace. The magnitude of average vertical and lateral range of the finger's displacement changed between paces (Figure 6), with evidence of a link to the adjustment of shoulder and hip roll magnitude between paces.

The elbow angle at the conclusion of the backward push was the only elbow angle variable to change between paces (Figure 7) and it is unlikely that the elbow angle contributed to the altered trajectory of the finger.
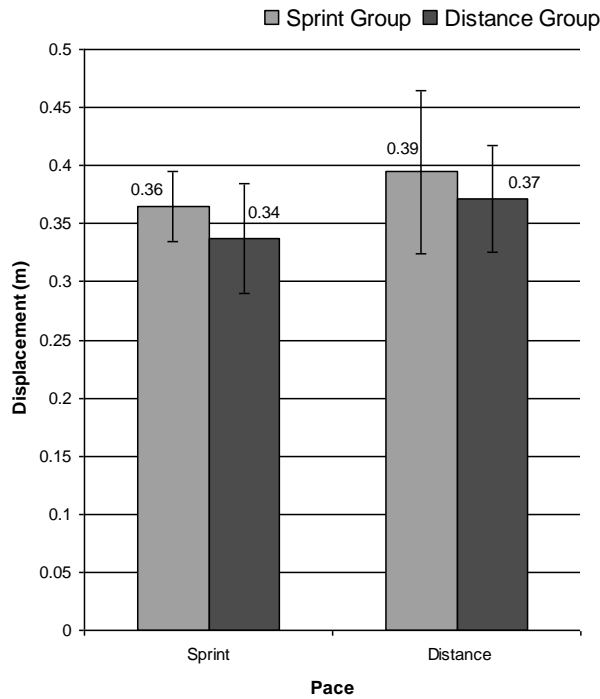
Figure 6: Average vertical displacement of the finger throughout the underwater stroke phase: Sprint group vs. distance group.
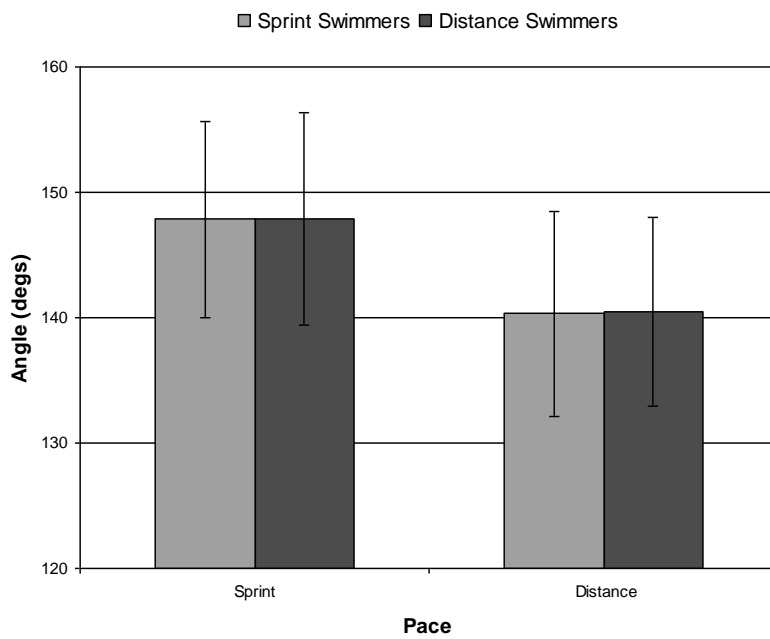
Figure 7: Comparison of elbow angle at the end of the push at sprint and distance paces. Both groups had a greater angle when sprinting.

The temporal aspects of the stroke trajectory also changed between the paces, primarily due to the varied duration of the entry phase. Specifically, the duration of the entry phase was approximately 10% longer when swimming at distance pace relative to sprinting. Maximum stroke depth and the

execution of the catch position were both attained 10% later in the SC when distance swimming (Figure 8). Contrary to the extant literature, the catch position did not differ between swim groups, but did change between swim paces. This finding challenges the existing knowledge of the catch position and requires further examination.
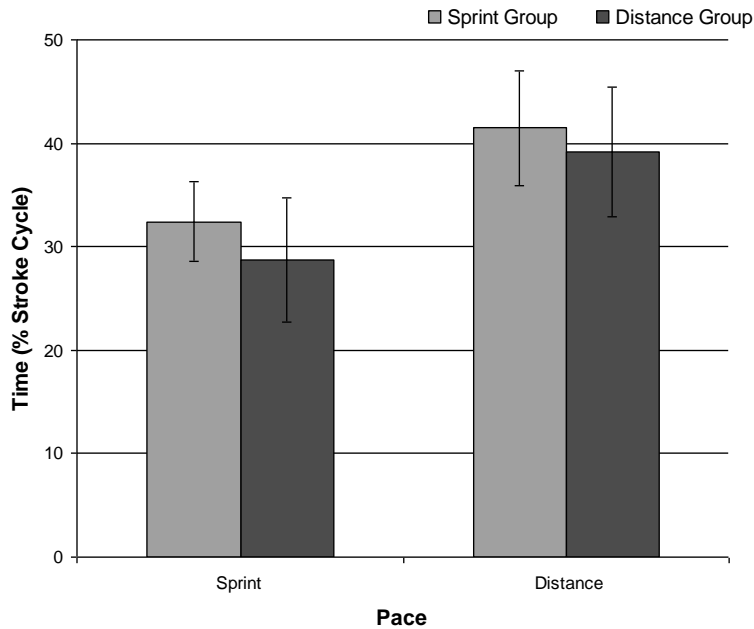

Figure 8: Time (% SC) corresponding to the catch for both swim groups, swimming at sprint and distance pace.

Finally, foot ROM changed between sprint and distance paces. Adrian et al. (1966) suggested that this occurs due to the energy requirements of the race distance. The magnitude of hip and shoulder roll appeared to be strongly influenced by the contribution of the leg kick between paces (Figure 9 and 10).
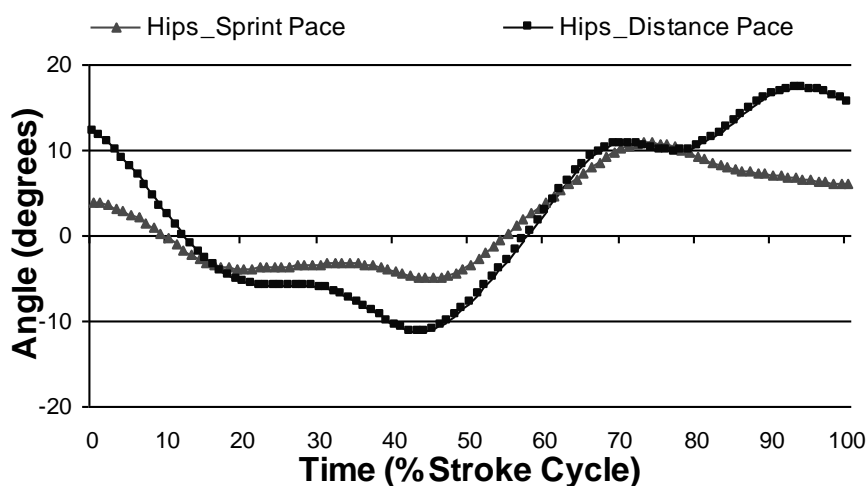
Figure 9: Time (%SC) to maximum left (negative) and right (positive) hip roll for the SG.
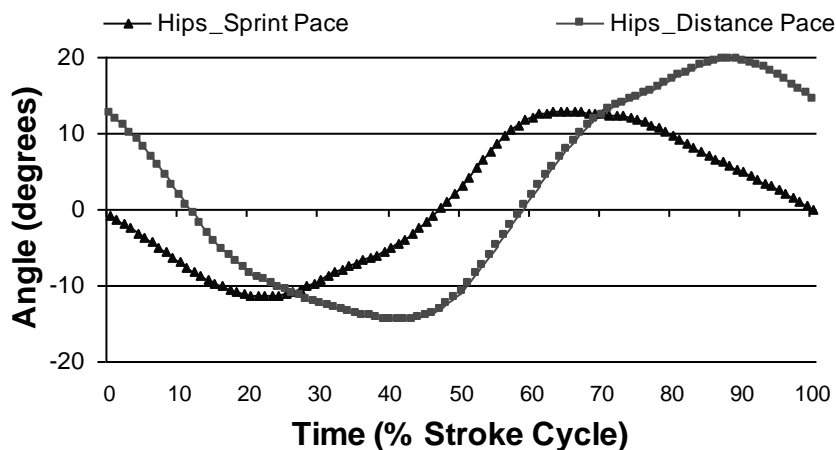
Figure 10: Time (%SC) to maximum left (negative) and right (positive) hip roll for the DG.

Rhythm in Front Crawl Swimming: Athletes and coaches frequently use the term 'rhythm'. If rhythms are regarded as being represented by sinusoidal waveforms, an assumption that fits well with dynamical systems theories of movement control incorporating limit cycle oscillators (e.g. Kelso, 1995), then Fourier analysis is a powerful tool to quantify rhythms. Fourier analysis represents any time series data, for example a displacement/time signal, as a series of waveforms. Each waveform (harmonic) is an integer multiple of the fundamental frequency. For example, if the fundamental frequency is 1hz, then harmonics occur at 2hz, 3hz…nhz. Fourier analysis determines the amplitude of each of those contributing waveforms and the 'phase', that is, the timing of when the peaks of the wave are attained.

To investigate the complex situation of the whole stroke that incorporates a roll about the long axis three-dimensional data were obtained from seven adult squad level swimmers simulating a 200m race (Sanders and Psycharakis, 2008). The upper body roll consists of a roll to either side, that is, a two beat pattern with one maximum and one minimum. Each arm action is likely to produce a maximum and minimum torque about the longitudinal axis. Given that there are two arm actions this may produce a four beat pattern with two maxima and two minima. As its name implies, the six beat kick consist of three upbeats and three downbeats of each leg that are out of phase thereby producing three maxima and three minima. In the full front crawl stroke, rather than being confined to a vertical plane as in flutter kicking without upper body roll and arm action, the lower limbs scribe an arc and their motion can be regarded more appropriately as a rolling action about the longitudinal axis. Thus, it is possible that the resultant waveforms associated with the rolling actions of the whole body comprise two beat, four beat, and six beat influences and, if very rhythmical in nature, may be reflected in three sinusoids represented as Fourier harmonics, these being the fundamental frequency (H1) with one maximum and one minimum, the second harmonic (H2) with two maxima and two minima, and the third harmonic (H3) with three maxima and three minima.
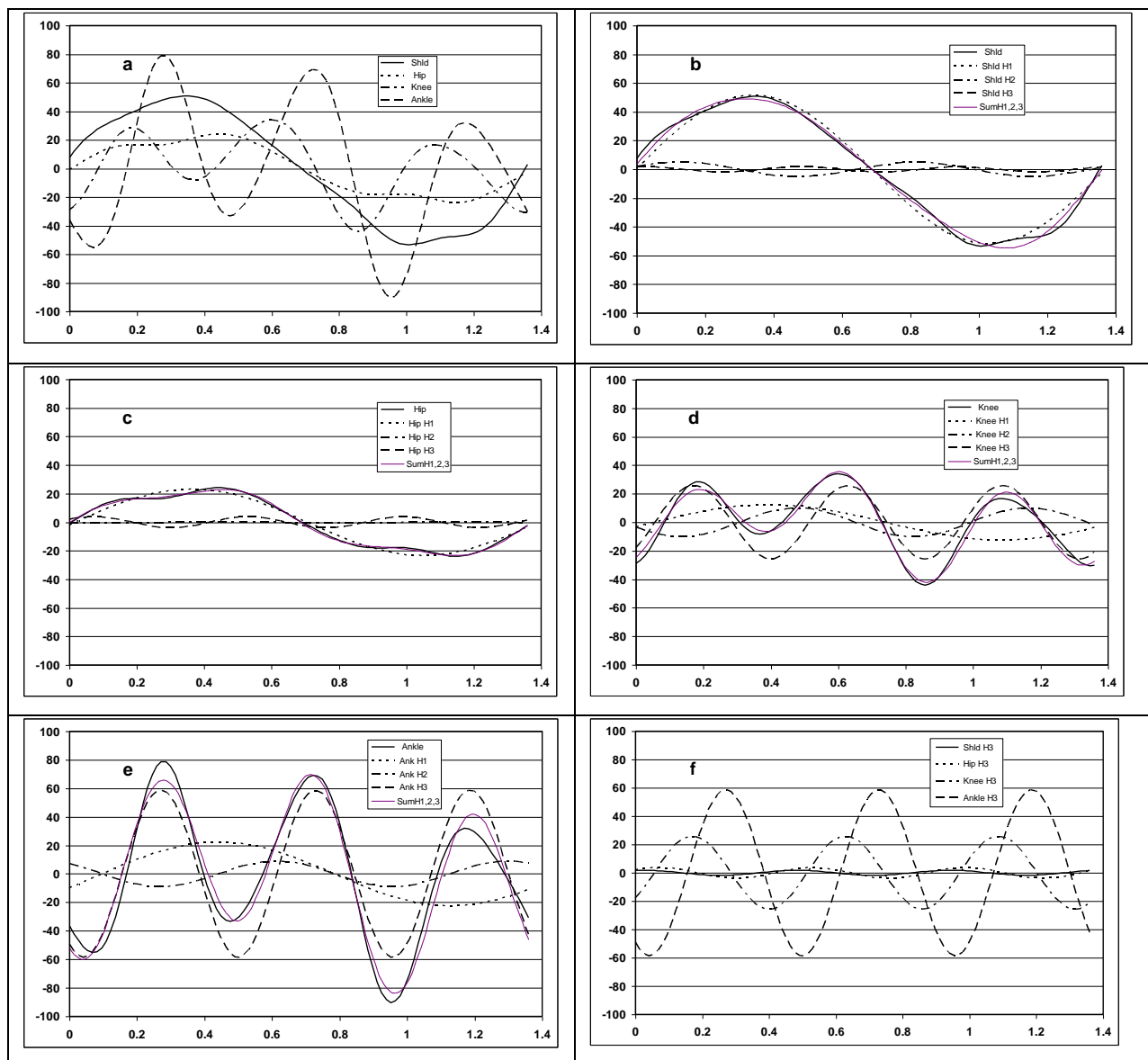
Figure 11. Rotation about the longitudinal axis (degrees) plotted against time (s) for one cycle of the best swimmer (S1) of a) shoulder, hip, knee, and ankle; b) shoulder and its H1, H2, and H3 contributions and sum of H1, H2, and H3; c) hip and its H1, H2, and H3 contributions and sum of H1, H2, and H3; d) knee and its H1, H2, and H3 contributions and sum of H1, H2, and H3; e) ankle and its H1, H2, and H3 contributions and sum of H1, H2, and H3; f) H3 of shoulder, hip, knee, and ankle.

Figure 11 shows the rotations about the longitudinal axis of the shoulders, hips, knees, and ankles, and the contributions of the H1, H2, and H3 harmonics for the best swimmer. Figure 11a shows that the shoulders rolled approximately 50 degrees to each side while the hips rolled only 22 degrees to each side. The amplitude of roll increased at the knees and reached about 80 degrees to each side in the ankles. Figures 11b to 11e show the contribution of the harmonics to the rolling action of each body part. The shoulder roll was very rhythmical with approx 98% of the power contained in a single sinusoid corresponding to the frequency of the stroke cycle. It is largely unaffected by the kicking

action. The hip roll is also dominated by H1 but there is some of H3 in reaction to the kicking pattern. The roll of the lines joining the knees is predominantly H3 due to the six beat kicking action but also contains considerable power in H1 indicating the influence of the upper body roll. The same applies, but to a lesser extent to the ankles. While the roll is dominated by H1 and H3, the power contained in H2 in the knee and ankle roll is not insignificant. It is due to the effect of the arm action occurring twice, that is two arm pulls, per cycle.

Only the H3 wave is transmitted in a consistent manner. The very high wave velocity for the H1 wave from shoulder to hip indicated that the shoulder and hip roll were almost exactly in phase. In contrast, the much slower wave velocity for H3 from hip to knee and from knee to ankle indicates a sequencing of the lower limb actions such that the H3 wave is transmitted in a cephalo-caudal direction. The sequencing is indicated by the differences in the times at which the H3 waves reach their peak for the hips, knees and ankles (11f). Small within and between subject variability in wave velocity indicated that this rhythmic pattern is characteristic of skilled front crawl swimmers using a six beat kicking pattern. The moderate H3 wave velocity, accelerating as it moves caudally, is consistent with the effective production of propulsion observed in marine animals (Sfakiotakis et al., 1999).

Figure 12 shows the velocity of the H3 wave from hip to knee (a) and from knee to ankle (b) for each of the four laps for each of the seven swimmers analysed. The four best swimmers had slower wave velocities than the other three swimmers. This in interesting in view of research with marine animals in which wave velocities of the caudal fins of the animals is only slightly faster than the swimming speed reflecting great efficiency (Sfakiotakis et al., 1999). The slight increase in wave velocity from knee to ankle relative to hip to knee among the best swimmers is in keeping with the goal of generating propulsion in an efficient manner.
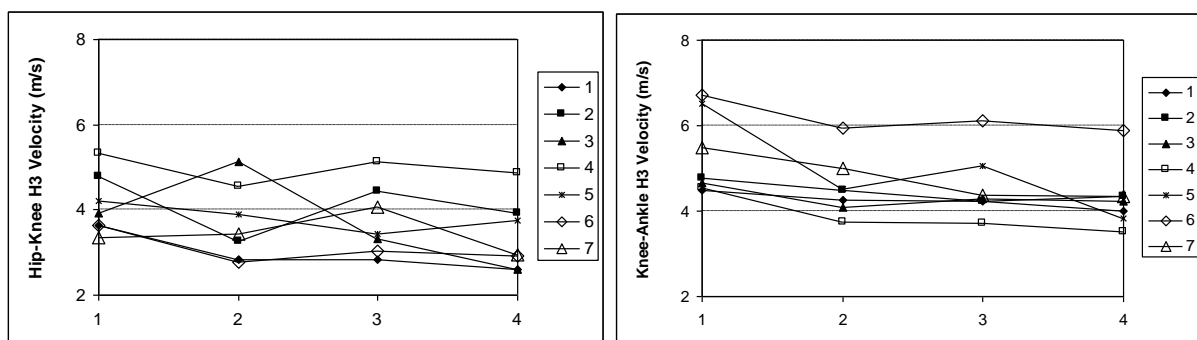
Figure 12. Line graphs of a) hip-knee H3 wave velocity and b) knee-ankle H3 wave velocity for each swimmer. Swimmers are ranked from fastest (S1) to slowest (S7).

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