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Rolling rhythms in front crawl swimming with six-beat kick

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ABSTRACT

The purpose of this study was to establish the rhythm characteristics of skilled front crawl swimmers using a six-beat kick. These included the amplitudes of the first three Fourier harmonics (H1, H2, H3) and their percent contributions to power contained in the angular displacement signals of the shoulders, hips, knees, and ankles with respect to the longitudinal axis in line with the swimming direction. Three-dimensional video data of seven national/international level swimmers were collected during simulated 200 m front crawl races in which swimmers maintained six-beat kicking patterns. Swimmers differed in all variables but had small variability across the four 50 m laps. Modest changes occurred during the 200 m, with the exception of shoulder roll, which remained constant and was represented almost entirely by a single sinusoid (H1). Changes across laps reached significance for swimming speed, stroke rate, hip roll, and H3 wave velocity between the knee and ankle. A H3 body wave of moderate and increasing velocity travelled caudally from hip to ankle. In the light of existing knowledge of aquatic locomotion this was compatible with the goal of generating propulsion in an efficient manner.

1. Introduction

Sinusoidal rhythms have become increasingly recognised as characteristic of human movement (e.g. Kelso, 1995) and offer the possibility of representing complex movement in simple low-order functions. Differences in phase among the sinusoidal motions of the body segments and joints give rise to the possibility that sinusoidal waves travel along parts of the body in a consistent and predictable manner. Sanders et al. (1995) found that the motion of elite butterfly swimmers was characterised by sinusoidal vertical undulations sequenced so that a body wave with the frequency of the stroke cycle (H1) progressed along the entire body at a rate slightly faster than the swimmer's speed. A body wave of twice that frequency (H2) travelled from the hip to the ankle at a faster rate. Further, in keeping with the goal of reducing the complexity of movement, the essence of the movement was captured in two sinusoidal waves with H1 and H2 accounting for over 98% of the power in the vertical motions of the body segments.

There is a lack of information in the extant literature regarding the rhythms in front crawl swimming. In butterfly swimming the sinusoidal components of the vertical undulations of the joints are associated with rotations of body segments predominantly about transverse axes perpendicular to each swimmer's vertical plane aligned with the direction of intended motion. However, the motion in front crawl swimming is complicated by the out of phase motion of left and right sides and by rotations about longitudinal axes.

In prone flutter kicking without arm action and without body roll a body wave in the vertical plane aligned with the direction of swimming motion travels caudally from hip to ankle (Sanders, 2007). In beginning swimmers the phase difference between hip and knee vertical undulations was smaller than among skilled swimmers. This meant that the mean velocity of the body wave travelling from hip to knee reduced from 8.2 m s^{-1} for the beginners to 2.8 m s^{-1} for the skilled swimmers. Among skilled swimmers the knee to ankle velocity of 3.2 m s^{-1} was slightly faster than the hip to knee velocity. Although the body wave velocity (relative to the moving body) from hip to ankles was considerably faster than the forward motion of the swimmer (<1 m s^{-1}) the trend towards slower body wave velocities and increasing swimming velocity with increasing skill is interesting in the light of the motion of marine animals. Efficient propulsion from caudal transmission of body waves in marine animals is characterised by wave velocities relative to the body that are slightly faster than the animal's forward motion with a tendency to increase as it progresses caudally (Sfakiotakis et al., 1999).

In the complete front crawl stroke additional rhythms associated with the roll of the upper body about its long axis and the actions of the arms may influence the composition of the

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waveforms characterising the motion of the hips, knees, and ankles. While several studies have investigated body roll (e.g. Payton et al., 1999; Yanai, 2003) there is an extreme lack of studies of body roll in terms of the rotations of all segments about a principal longitudinal axis. Further, two studies (Cappaert et al., 1995; Psycharakis, 2006) investigating body roll using three–dimensional (3D) analysis techniques have indicated that the hips and shoulders move through different ranges and reach their maxima at different times. The fact that shoulders and hips roll with some independence from each other opens the possibility of sequencing and, as in the case of butterfly swimming, the transmission of body waves.

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.

The purpose of this study was to investigate the rhythm characteristics of skilled front crawl swimmers with respect to rotations about a longitudinal axis aligned with the direction of intended motion.

2. Methods

2.1. Participants

Seven male freestyle swimmers who specialise in 200 m freestyle, use a six-beat kick throughout their 200 m races, and compete at national/international level participated in this study (age: 17.0 ± 1.0 years; height: 181.0 ± 2.8 cm; body mass: 70.7 ± 3.0 kg; personal best performance in the 200 m freestyle: 123.1 ± 5.5 s).

2.2. Protocol

All tests were conducted in a 25 m indoor pool. Each swimmer performed a 200 m maximum freestyle swim using his exact competition pacing and strategy. The 200 m distance was chosen as it enables an assessment of consistency in the rhythms and whether rhythms change throughout a race as a swimmer's pace and level of fatigue changes. Swimmers were recorded by six stationary and synchronised JVC KY32 CCD cameras (four below and two above the water) as they swam through a calibrated space 6.5 m long. The calibration set-up and the accuracy and reliability procedures have been described in detail by Psycharakis et al. (2005). A push start was used to eliminate the influence of the dive on the kinematics analysed for the first length. To eliminate any effects of breathing on rhythms, swimmers were instructed to avoid breathing while swimming through the pre-calibrated space. This overcame the possibility of within swimmer variability being increased due to the random capture of breathing versus non-breathing cycles and breathing to left and right sides.

2.3. Data processing

One stroke cycle, defined as the period from entry of one hand to the subsequent entry of the same hand was recorded near the 15 m mark of each 50 m length and, therefore, each variable of interest was calculated for one stroke cycle in each 50 m lap (Lap1, Lap2, Lap3 and Lap4) throughout the 200 m. Pilot work had established that by the time swimmers entered the calibrated volume they had established regular and consistent stroke kinematics that accurately reflected their mid-pool swimming. Nineteen body landmarks (vertex; shoulder, elbow, wrist, hip, knee, ankle and metaphalangeal joints; the end of the middle fingers and the big toes) were marked with circles of permanent black marker 2 cm in diameter and manually digitised for each field (50 fields per second) using the Ariel Performance Analysis System (APAS). A 3D reconstruction was performed using the Direct Linear Transformation method (Abdel-Aziz and Karara, 1971) incorporated in APAS. 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.

The above and below water sequences were digitised and transformed separately. The different sequences were then combined into a single file. A Fourier transform and inverse transform were used to smooth the raw displacement data by retaining harmonics up to 6 Hz in the inverse transform.

2.4. Data analysis

The roll angles of the shoulders, hips, knees, and ankles were determined by projecting the vector of the respective right joint relative to the left joint onto the vertical plane perpendicular to the swimming direction. Computationally this was the arctangent of the ratio of Z and Y (transverse and vertical axis) vector coordinates with standard corrections to account for quadrant.

Fourier analysis was used to determine amplitude and phase of angular displacement-time signals for each of the contributing harmonics.

Amplitude (C) of each frequency was obtained by

$$Cn = (\mathrm{An}^2 + \mathrm{Bn}^2)^{0.5}$$

where An and Bn are the cosine and sin coefficients for the *n*th Fourier frequency (harmonic).

The phase angle was calculated by

$$\theta = \tan^{-1}(\mathrm{Bn}/\mathrm{An})$$

The contribution by each frequency to the mean squares value of average power of the signal was given by $2Cn^2$.

The velocity of wave travel (v) between shoulders and hips, hips and knees, and knees and ankles, was determined for the dominant frequencies using the relationship

$$v = d/t$$

where d is the displacement between the mid points of the shoulders and hips, hips and knees, and knees and ankles and t is the time taken for the oscillation of the more caudal landmark to achieve the same phase as the more cephalic landmark. Time was calculated as

$$Tm = (\theta_m - \theta_{m+1})T/360$$

where θ_m is the phase angle of the *m*th body landmark (numbers increasing in the cephalo-caudal direction) and T is the period of the cycle. The average swimming velocity was obtained as the displacement in the *X*-direction of the midpoint of the hips during the stroke cycle divided by the duration of the stroke cycle.

Reliability of the measures was obtained by digitising one complete stroke cycle of one swimmer five times for all six cameras. For each calculated variable, the standard deviation (SD) across all digitisations indicated the reliability.

2.5. Statistical analysis

Means and SDs were determined for the variables of interest across all swimmers and 50 m laps, across swimmers for each 50 m lap and across laps for each swimmer. Repeated measures ANOVAs with post hoc pairwise comparisons of all six pairs of laps were conducted. Given the multiple tests the critical p value was reported as 0.0083, being the Bonferroni adjustment (Vincent, 2005) for a confidence limit of 0.05. However, this did not preclude interpretation of low p values above the critical value contributing to a 'weight of evidence'. For all the repeated measures ANOVAs, the assumption of sphericity was tested. Given that this assumption was not violated, no further data adjustments were required. All statistical analyses were conducted with the use of the Statistical Package for Social Sciences (SPSS) 14.0 software.

3. Results

3.1. Reliability

Reliability of the measures of frequency composition, roll, phase difference and wave velocity is presented in Table 1. For all