Stroke frequency in front crawl: its mechanical link to the fluid forces required in non-propulsive directions

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Abstract

Two hypotheses were tested: (a) stroke frequency is predictable from the amplitudes of bodyroll and the turning effect around the body’s long-axis generated by the non-propulsive fluid forces (that is, the torque driving bodyroll), and (b) swimmers exhibit at least one alteration in the factors influencing the bodyroll cycle as they increase the stroke frequency for faster swimming, so that they can reduce the fluid forces “wasted” in non-propulsive directions. The mechanical formula that links stroke frequency and the kinetics of bodyroll was derived on the basis of Euler’s equation of motion. Experimental data were collected from competitive swimmers to validate the derived mechanical relations and to examine the strategy that skilled swimmers would use to change the stroke frequency as they swim faster. A strong correlation (slow: \( r = 0.70 \) and fast: \( r = 0.85 \)) and a non-significant difference between the observed stroke frequency and the formula-based estimates supported the first hypothesis. As the subjects increased stroke frequency (38%) for faster swimming, bodyroll decreased (19%) and the trunk twist increased (40%). The combined alterations resulted in a small reduction in the shoulder roll (12%), enabling the swimmers to gain the benefits associated with a large rolling action of the upper trunk, while limiting the amount of increase in the turning effect of fluid forces in non-propulsive directions (40%). The second hypothesis was, therefore, supported. The derived mechanical formula provides a theoretical basis to explore mechanisms underlying the interrelations among stroke frequency, stroke length and swimming speed, and sheds light on a possible reason that swimmers generally adopt six-beat kicks.

Keywords: Bodyroll; Euler’s equation of motion; Principal moment of inertia; Six-beat kick; Three-dimensional videography

1. Introduction

Front crawl is the fastest form of human locomotion in an aquatic environment. The world records in the freestyle events, in which most swimmers, if not all, use the front crawl technique, demonstrate the level of sophistication in the skill of human locomotion in water. Competitive swimmers train to use the complex time- and position-dependent fluid force system effectively, so that they can maximize the distance travelled with one stroke cycle (stroke length) and the rate at which the stroke cycle is repeated (stroke frequency). The stroke length and stroke frequency of competitive swimmers have been investigated by many researchers (Arellano et al., 1994; Costill et al., 1991; Craig and Pendergast, 1979; Craig et al., 1985; East, 1970; Hay et al., 1983; Kennedy et al., 1990; Pai et al., 1984; Wakayoshi et al., 1993), the results of which suggest that a given swimmer swims faster in short term (e.g. on a given day) by increasing stroke frequency and that the same swimmer improves the maximum swimming speed in long term (e.g. over a season of training) by increasing the stroke length (Hay, 1993). The latter implies that the swimmers learn over a period to swim at a given speed with a reduced stroke frequency.

Intuitively, stroke frequency seems to be determined by the swimmer’s internal effort of moving the arms at a desired frequency. Hay (1993) listed three factors as major determinants of stroke frequency: (a) the moment of inertia of the arm about the shoulder, (b) the range of motion through which the arm moves and (c) the torque applied to the arm through the shoulder. In front crawl, however, modifications of these three factors may not guarantee an increase in the stroke frequency because the arm movement in front crawl must be incorporated

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with the rolling action of the trunk about its long axis. An increase in stroke frequency must, therefore, be accompanied by a corresponding increase in the frequency of the trunk roll cycle.

The trunk roll is driven by two distinct sources of torque (Fig. 1): The turning effect of external (fluid) forces that generates the rolling of the entire body with respect to the global reference frame and the turning effect of internal forces that generates the rolling of the trunk relative to the principal axes of the entire body. Yanai (2001) found that the trunk roll exhibited by competitive swimmers was attributed primarily to the turning effect of the external forces rather than that of the internal forces. This result indicates that competitive swimmers generate, consciously or unconsciously, a suitable amount of external force to match the rolling cycle of the entire body with the arm movement cycle. Because the external forces that generate the roll of the entire body must act in vertical or medio-lateral directions (non-propulsive directions), the required matching imposes a constraint on the swimmers that may limit swimming propulsion and efficiency. This line of logic sheds additional light on the mechanism of interrelations among stroke frequency, stroke length and swimming speed, providing a foundation to advance the level of sophistication of front crawl technique. Two hypotheses were tested in the present study: (a) stroke frequency is predictable from the amplitudes of bodyroll and the turning effect around the body's long-axis generated by the non-propulsive fluid forces and (b) swimmers exhibit at least one alteration in the factors influencing the bodyroll cycle as they increase the stroke frequency for faster swimming, so that they can reduce the fluid forces “wasted” in non-propulsive directions.

2. Methods

In the present study, the term “bodyroll” described the rolling action of the swimmer’s body due to the turning effect of the external (fluid) forces (Fig. 1, center). Specifically, the angular displacement of the entire body about its longest principal axis defined bodyroll. Although the definition of the swimmer’s whole body angular displacement had only a conceptual, but no physical, significance because of a swimming human body not being a single rigid system, an effort was made to calculate a single representative value of “bodyroll” that could allow an establishment of mechanical link between the stroke frequency and the turning effect around the long-axis generated by the fluid forces, and comparisons across subjects (computational details are described later).

The mechanical link between the stroke frequency and the turning effect of fluid forces required for a given rolling cycle of the entire body was defined on the basis of Euler’s equation of motion in four steps: First, the bodyroll cycle was modeled and expressed as an angular displacement vs. time relation. As apparent from the movement pattern of front crawl, bodyroll was expected to exhibit a sinusoidal pattern of change with respect to time (Fig. 2), expressed as

\[
\text{Bodyroll}(t) = \text{BR}_{\text{MAX}} \sin\left(\frac{2\pi t}{T}\right) \tag{1}
\]

where \(\text{BR}_{\text{MAX}}\) is the maximum bodyroll angle (rad), \(T\) the stroke time (s) and \(t\) the time measured with respect to an instant at which \(\text{Bodyroll} = 0\).

Second, the moment of inertia of the entire body about the long-axis, \(J_1(t)\), was modeled. Its changing pattern should exhibit two cycles in a stroke as the body

![Fig. 1. Two sources of torque that drive trunk roll. First, the turning effect of external (fluid) forces acting on the body that causes the entire body to roll with respect to the global frame of reference; and second, the turning effect of internal forces acting within the body that causes the trunk to roll with respect to the principal axes of the entire body. In the present study, the rolling action of the entire body due to the fluid forces is defined as bodyroll.](image-url)
mass distributes away from the long-axis during the two recovery phases (Fig. 2). Thus, the first time derivative of the product of the angular velocity of bodyroll and the moment of inertia was expected to exhibit two sinusoidal patterns in a stroke cycle. As apparent from the illustrations of a swimmer in the view from the front, bodyroll was expected to exhibit a sinusoidal pattern of change at the stroke frequency. The changing pattern of whole body moment of inertia was expected to exhibit two sinusoidal patterns in a stroke cycle as the body mass distributes away from the long axis during the two recovery phases. The external torque was derived analytically as the first time derivative of the product of the angular velocity of bodyroll and the moment of inertia.

\[ J_L(t) = J_{L-MEAN} - J_{L-AMP} \cos(4\pi T + \beta), \]

where \( J_{L-MEAN} \) is the mean value, \( J_{L-AMP} \) the amplitude of the fluctuating moment of inertia \( J_{L-MAX} = \frac{1}{2}(J_{L-MAX} - J_{L-MIN}) \) and \( \beta \) the phase lag between \( J_L(t) \) and Bodyroll(t).

Third, the turning effect of fluid forces \( [Tq(t)] \) was analytically derived as follows:

\[ Tq(t) = \frac{d(J_L \omega_L)}{dt} - (J_F - J_T) \omega_T \omega_F, \]

where \( \omega_L, \omega_F \) and \( \omega_T \) are the angular velocities of the entire body about long, frontal and transverse axes, respectively, and \( J_F \) and \( J_T \) are the moments of inertia about frontal and transverse axes, respectively. Because the product of the angular velocities \( \omega_T \) and \( \omega_F \) was expected to be small in front crawl, the second term on the right-hand side of the equation was assumed to be zero. This assumption made the effect of fluctuating \( J_F \) and \( J_T \) of the swimmers on the torque insignificant. Replacing \( \omega_L \) by \( \omega_{BR} \) the angular velocity of bodyroll \([= \text{d Bodyroll(t)}/\text{dt}]\) resulted in:

\[
Tq(t) = -J_{L-MEAN} \omega_{BR} (2\pi T)^2 \sin(2\pi T/T)
+ 5J_{L-AMP} \omega_{BR} (2\pi T)^2 \sin(2\pi T/T) \cos \beta
- 6J_{L-AMP} \omega_{BR} (2\pi T)^2 \sin^3(2\pi T/T) \cos \beta
+ 2J_{L-AMP} \omega_{BR} (2\pi T)^2 \cos^2(2\pi T/T) \sin \beta
- 6J_{L-AMP} \omega_{BR} (2\pi T)^2 \sin^2(2\pi T/T) \cos (2\pi T/T) \sin \beta.
\]

Finally, the formula at the global maximum \((t = T/4)\) with zero phase lag \((\beta = 0)\) was extracted and rearranged into a simple formula that expressed the mechanical link between the stroke frequency and the turning effect of fluid forces around the body’s long-axis,

\[
SF = \frac{1}{T} = \sqrt[2]{\frac{Tq_{MAX}}{J_{L-MEAN} + J_{L-AMP} \omega_{BR} (2\pi T)}}.
\]

This formula dictates that stroke frequency (SF) is proportional to the square root of the turning effect of fluid forces \( (Tq_{MAX}) \) and inversely proportional to the square root of the maximum bodyroll \( (BR_{MAX}) \).

An experiment was conducted to test the validity of the derived mechanical formula and to examine the strategy that swimmers used to change the stroke frequency. A three-dimensional videography technique with panning periscopes (Yanai et al., 1996) was used for the data collection. Eleven members of a collegiate men’s swimming team were asked to perform front-crawl at a moderate pace (speed = 1.3 ± 0.1 m/s) and a sub-maximum sprinting pace (speed = 1.6 ± 0.1 m/s). No instruction was given to the subjects regarding the stroke frequency, so that they were able to adopt the stroke frequency that they felt comfortable and natural for the given speeds of performance. The performances were recorded by camcorders (Panasonic AG 450-SVHS) fixed to the respective periscopes (Fig. 3). The periscopes were located approximately 20 m away from the subjects, and the distortion of the recorded images due to refraction (Kwon, 1999) was minimal. The procedure for data collection was approved by the Human Subject Review Committee and each subject provided written informed consent.

The videotapes of the performances were manually digitized for every field (60 fields/s) using a Peak 2D System (Peak Performance Technologies, Denver, CO, USA) for one stroke cycle. In each field, 21 body landmarks were digitized to represent the end points of each of 14 segments of a human body model which consisted of head, torso, upper arms, forearms, hands, thighs, shanks and feet (digitize–redigitize reliability was...
high \( r > 0.98 \)). The resulting sets of two-dimensional coordinate data were then transformed into the corresponding three-dimensional coordinates on the basis of a DLT-based algorithm (Yanai et al., 1996). The length of each segment determined from the video recordings was subject to a mean error of \(< 3\%\). The coordinates were expressed with respect to a global reference frame (GRF) with origin ‘O’ located at the surface level of the pool when the water was still and undisturbed (Fig. 3).

The three-dimensional coordinates were smoothed using a fourth order, zero lag, low-pass Butterworth filter (Winter et al., 1974) with various cut-off frequencies (2–4 Hz). The cut-off frequencies were set so that approximately 95\% \((\pm 3\%)\) of the power of the original signal could be retained in the filtered signal.

The \(3 \times 3\) mass–center inertia matrix of the entire body about three orthogonal axes parallel to the GRF and passing through the CM \((J_{CM})\) was determined from the following equation (Haug, 1992):

\[
J_{CM} = \sum_{i=1}^{14} (A_i/GRF J_i A_i^{T}/GRF + m_i (r_i^{T}/CM I - r_i/CM r_i^{T}/CM)),
\]

where \(A_i/GRF\) is the \(3 \times 3\) rotation matrix to represent the orientation of the segment \(i\) with respect to the GRF, \(J_i\) the \(3 \times 3\) diagonal matrix for the principal moment of inertia of segment \(i\), \(m_i\) the mass of the segment \(i\), \(r_i/CM\) the position vector pointing from the whole body center of mass to the center of mass of the segment \(i\), and \(I\) the \(3 \times 3\) identity matrix.

All body segments were assumed to be symmetric about their own long axes. The principal moment of inertia of each body segment \((J_i)\) required for the computation was estimated by normalizing and scaling the data presented by Whitsett (1963) in accordance with the method described by Dapena (1978). The segmental masses and the relative position of each segmental CM were estimated from the data presented by Clauser et al. (1969) and Hinrichs (1990). The moment of inertia of the entire body about its long axis \((J_L)\) and the unit vector representing the long axis of the entire body were determined for every field as the smallest eigenvalue of \(J_{CM}\) and the corresponding eigenvector, respectively. A computer subroutine “jacobii” (Press et al., 1992, pp. 460–461) was used for this computation.

Bodyroll was determined for every field as the time integral of the angular velocity of the entire body about the long axis, which, in turn, was determined from the angular momentum of the entire body about the long axis and the \(J_L\). The determined bodyroll, therefore, represented the angular displacement that a single rigid body possessing the same mass and mass distribution as the swimmer’s body would have to exhibit in order to have the same angular momentum about the CM of the body that the swimmer’s body possessed. The initial value for the integration was chosen, so that the mean value of bodyroll over one complete cycle became zero. The turning effect of the fluid forces around the long axis was determined as the dot product of the time derivative of the angular momentum vector and the unit vector representing the long axis. The angular momentum of the entire body about three orthogonal axes passing through the CM was computed with the procedure described by Dapena (1978) with two modifications. First, the trunk segment was subdivided mathematically into two sections—upper and lower halves—connected through the mutual long-axis. Each of the two sections had an identical value for the moment of inertia about the center of mass of the entire trunk \((J_{Trunk}/2)\). The rotations of the upper and lower halves of the trunk about the long-axis were determined as shoulder roll (SR) and hip roll (HR) angles, respectively. The angular momentum of the entire trunk about its long axis \((H_{Trunk})\) was therefore determined as follows:

\[
H_{Trunk} = [J_{Trunk} (\omega_{SR} + \omega_{HR})]/2,
\]
where $\omega_{SR}$ and $\omega_{HR}$ are the angular velocities of SR and HR, respectively.

The second modification was that the angular velocities of the head and limb segments about their long axes were not assumed to be zero but estimated from the angular velocity of the trunk, in accordance with the method described by Dapena (1997).

Fig. 4. The changing pattern across subjects for bodyroll (top), whole body moment of inertia (middle) and external torque (bottom) for moderate pace swimming (left) and sub-maximal sprinting (right) for one stroke cycle. Each set of time-series data represents the average values across all subjects for time-normalized, phase-adjusted data: time was normalized with respect to the stroke time for each subject, and the phase was adjusted using cross-correlation analysis to have the bodyroll cycle synchronized for all subjects (the phase difference between bodyroll cycle and moment of inertia cycle was not adjusted). (Note: The maximum and minimum values attained in the observed data were not identical to the corresponding values in the modeled data because: (a) the average value over the stroke cycle for a given observed data set was not necessarily equal to the average between the maximum and minimum values taken from the same data set, and (b) the instants at which a series of maximum and minimum values were attained in the observed data were not always identical to the corresponding instants in the modeled data, and the difference in timing of these instants was not constant across subjects even after the phase adjustment.) The time-series data modeled with the mechanical formulae matched closely the corresponding data obtained experimentally, indicating that the changing patterns of the variables were well represented by the simple mechanical functions. The $r$-values are correlation coefficients between the observed and modeled data and the $\varepsilon$-values indicate the relative difference between the two for the ith field computed with the following formula:

$$\sqrt{\frac{\sum (\text{Modelled}_i - \text{Observed}_i)^2}{\sum \text{Observed}_i^2}}$$

where $\text{Modelled}_i$ and $\text{Observed}_i$ are the observed and modeled values for the ith field.
The validity of the mechanical formula that links the stroke frequency and the turning effect of fluid forces (Eq. (5)) was tested by comparing the experimentally obtained values of stroke frequency with the formula-based estimates by means of correlation analysis and paired t-test. The standard formula \( SF = 1/T \) was used to determine the experimental value of stroke frequency. The stroke time \( T \) in this computation was measured as the duration between two successive arm entries on the same side. The formula-based estimates were determined with four experimentally determined bodyroll-related variables \( (BR_{MAX}, J_{L\text{-}MEAN}, J_{L\text{-AMP}} \text{ and } Tq_{MAX}) \) as input. The strategy that the swimmers used to change the stroke frequency was determined by conducting a series of paired t-tests for seven bodyroll-related variables (those listed above plus \( Tq_{MAX}, SR_{MAX}, HR_{MAX} \)) obtained for two swimming speeds. The statistical significance was assessed at 0.05 level.

3. Results

The mechanical formula was found valid and the stroke frequency was predicted well with a mechanical formula that involves the turning effect around the body’s long axis generated by the fluid forces in non-propulsive directions. All three time-series variables modeled with the mechanical formulae were highly correlated with the corresponding variables obtained for sub-maximal sprinting trials \( (r > 0.90) \), whereas the correlation was slightly weaker \( (r > 0.60) \) for moderate pace trials (Fig. 4). A strong correlation (Fig. 5) was found between the observed and the estimated stroke frequencies for both moderate pace \( (r = 0.70) \) and sub-maximal sprint pace \( (r = 0.85) \), and the mean difference between the observed and estimated stroke frequencies (Table 1) were not significantly different from zero. These results support the first hypothesis.

As the subjects increased their stroke frequency (by 38%) for the faster swimming pace, bodyroll was decreased by 19% (Table 2) and the trunk twist increased by 40% (Table 3). This combination of changes resulted in a small reduction in the shoulder roll (by 12%) and a limited increase in the magnitude of external torque (by 40%). The mechanical formula (Eq. (5)) indicate that the observed reduction in bodyroll has contributed to reducing the external torque required as the increased stroke frequency, and thereby, the second hypothesis is supported.

4. Discussion

Observations have consistently suggested that swimmers improve their performance over a period of training, being able to attain a faster speed with an increased stroke length: In other words, swimmers learn to swim at a given speed with a reduced stroke frequency. The present study was conducted to establish a mechanical foundation that linked the stroke frequency of front-crawl and the fluid forces required in non-propulsive directions, so that underlying mechanism of the observed interrelations among stroke frequency, stroke length and speed could be examined.

The methods used in the study involved three limitations: First, the mechanical formulae were derived on the basis of two-dimensional angular motion of the body with an assumption that the movements of the entire body about its frontal and transverse axes were small and the effect of it on the kinetics of bodyroll was negligible. This assumption was supported by the experimental data demonstrating that the entire body changed its orientation only by \( \pm 0.02 \) rad at <0.32 rad/s about the frontal-axis \( (\omega_F) \) and \( \pm 0.07 \) rad at <0.15 rad/s about the transverse axis \( (\omega_T) \), with a negligible effect on the kinetics of bodyroll. Hence, the application of two-dimensional analysis for bodyroll was justified. Second, the phase lag between the bodyroll cycle and the cycle of moment of inertia was assumed to be zero for the derivation of the formula that predicted...
On average, the phase lag was 3.6 ± 1.9% and 3.5 ± 1.9% of the stroke time for slow and fast trials, respectively. A sensitivity analysis (Fig. 6) indicated that the error in estimating stroke frequency due to the zero phase lag assumption was less than 0.002 strokes/s (<0.3%) for a range of ±10% in phase lag. In addition, the experimental data demonstrated that the formula estimated the stroke frequency with a high accuracy even for the subject whose phase difference was largest (7% of stroke time). These data suggest that the derived formula presents a simple but valid mechanical relation between the stroke frequency and the kinetics of body roll. Third, the calculated body roll represented the angular displacement of the body's principal axes generated exclusively by the fluid forces acting on the entire body, and thus, possible angular displacement of the principal axes generated by other mechanism (Fig. 7) was not taken into account. This might explain why the observed amplitude of body roll was smaller than the amplitudes of shoulder and hip rolls (Table 3). However, it allowed derivation of a simple mechanical formula linking stroke frequency and the fluid forces required for body roll.

The present study demonstrated that a simple formula described well the mechanical relations between stroke frequency and the factors influencing body roll, and that the stroke frequency was predictable with the formula. This finding indicates that the stroke frequency is controlled not only by the swimmer's internal effort of moving the arms at a desired rate, but also by the swimmer's ability to generate the fluid forces in non-propulsive directions to match the frequency of the body roll cycle with that of the arm movement cycle. The formula dictates that an increase in the stroke frequency requires a corresponding increase in the turn effect of non-propulsive fluid forces unless the amplitude of body roll is reduced substantially (Eq. (5)). It suggests that swimmers should adopt the lowest stroke frequency possible at given speeds of swimming, because a lowered
stroke frequency requires a reduced amount of fluid forces in the non-propulsive directions to maintain the same amplitude of body roll. This allows the swimmers to either increase the amplitude of body roll or learn to re-direct this surplus into the propulsive direction to swim faster. This postulated mechanism explains one possible reason for the observation that freestyle swimmers have improved their maximum swimming speed over a period of training by increasing their stroke lengths (Costill et al., 1991; Hay et al., 1983; Wakayoshi et al., 1993), because the observation indicates that the swimmers learned to swim at a given speed with a reduced stroke frequency. Longitudinal studies are indicated to examine the season-long changes in the stroke length–frequency relations and the propulsive efficiency, so that the above postulation can be evaluated.

The derived mechanical formula (Eq. (4)) provides a possible reason that swimmers generally adopt the so-called six-beat kick technique. With the six-beat kick technique, a downward thrust of the left leg coincides with the beginning of the recovery phase of the ipsilateral arm, the following downward thrust of the right leg is executed at the middle of the same recovery phase, and the second ownward thrust of the left leg is executed at the entry of the ipsilateral arm into the water (Fig. 8). This pattern is repeated on the other side of the body during the recovery phase. The turning effect of the fluid forces generated by these kicks is expected to exhibit three sinusoidal cycles in a stroke cycle. One component of the derived mechanical formula that is a
function of the fluctuating moment of inertia of the body has three sinusoidal cycles in a stroke cycle (Fig. 8). The timing of the three cycles and the six alternate directions of torque exactly match those expected from the six-beat kick technique. This perfect matching seems to explain why swimmers generally adopt six-beat kicks in front-crawl.

The present study also demonstrated that swimmers reduced the amplitude of bodyroll and increased the magnitude of trunk twist as they increased the stroke frequency for faster swimming. The increased trunk twist enabled the swimmers to attain a large rolling amplitude of the upper trunk (shoulder roll) so as to improve performance (Prichard, 1993) and to prevent shoulder injuries (Beekman and Hay, 1988; Ciullo and Stevens, 1989; McMaster, 1986; Neer and Welsh, 1977; Penny and Smith, 1980; Richardson et al., 1980). An increased trunk twist at high stroke frequency was also reported in a cross-sectional study of Olympic competitors (Cappaert et al., 1995), in which “sub-elite” swimmers exhibited a larger trunk twist (mean = 44°) at a higher stroke frequency (mean = 0.91 Hz) than “elite” swimmers (mean of 17° at 0.82 Hz), while both groups of swimmers attained nearly the same shoulder roll (mean of 35°). These findings suggest that competitive swimmers use the trunk-twisting motion effectively to gain the benefits associated with a large rolling action of the upper trunk and to prevent the amount of fluid forces “wasted” in non-propulsive directions for body-roll from increasing as a quadratic function of stroke frequency (Eq. (5)). It is not certain, however, how much reduction in the fluid forces required for bodyroll optimizes the performance because: (a) some fluid forces may well be generated as a result of kicks and the buoyant force acting eccentric to the long-axis during the recovery phases and (b) a large trunk twist may increase the resistance acting on the swimmer. Further studies are indicated to examine the strategy for optimizing performance by reducing the fluid forces wasted in non-propulsive directions.

The present study has established a mechanical foundation that links the stroke frequency in front crawl swimming and the fluid forces required in non-propulsive directions. This provides a theoretical basis to explore mechanisms underlying the interrelations among stroke frequency, stroke length and swimming speed that have been observed consistently over the years. Future studies are indicated to examine: (a) the influence of the non-propulsive fluid forces required to maintain the bodyroll cycle and propulsive efficiency and (b) the possible strategy to improve the technique of front crawl swimming by reducing the fluid forces wasted in non-propulsive directions.

Fig. 8. A possible reason that swimmers generally, and somewhat naturally, adopt six-beat kicking technique in front crawl swimming. (Note: The Eq. (4) with zero phase lag (\(\beta = 0\)) is used in this figure for simplification purposes.) One component of the turning effect of external forces is a function of the body’s fluctuating moment of inertia, which has three cycles in a stroke cycle. The timing of the three cycles and the six alternate directions of the torque exactly match those expected from the six-beat kick technique. For example, as the swimmer simultaneously kicks the left leg down and kicks the right up (first illustration), the hydrodynamic forces are expected to act upwards on the left leg and downwards on the right. These hydrodynamic forces generate a torque about the long-axis in the counter-clockwise (positive) direction in the view from the front. The bottom graph shows that this expected direction of the torque due to the kick matches the direction of torque indicated by the equation. This matching is also evident in the other five kicks executed in the same stroke cycle. It is postulated, therefore, that swimmers generally and naturally adopt six-beat kicks in front crawl, so that this component of torque can be generated by using the near-vertical fluid forces generated by kicks effectively, rather than by “wasting” the fluid forces generated by the arm strokes in non-propulsive directions.

References


