

BUOYANCY: THE PRIMARY SOURCE OF BODYROLL IN FRONT CRAWL SWIMMING

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The purpose of the study was to determine the rotational effect of buoyant force (buoyant torque) and its contribution to the bodyroll exhibited during front crawl swimming performed at a distance pace. Three-dimensional videography was used to measure the position and orientation of the body segments of eleven competitive swimmers performing at a distance pace. The buoyant torque was computed with the method described by Yanai (1999). The bodyroll generated by the buoyancy torque was determined from the double time-integral of the buoyancy torque and the principal moment of inertia of the body. The buoyancy torque changed in the mean range from -7.7 Nm to 7.7 Nm with a systematic pattern at stroke frequency. The buoyant torque generated the bodyroll of the peak-to-peak amplitude 1.26 radians, accounting for 88% of the peak-to-peak amplitude (mean = 1.43 radians) of the bodyroll exhibited by the swimmers.

KEY WORDS: angular velocity, buoyant force, 3D videography, principal axis, torque

INTRODUCTION: In front crawl swimming, swimmer's body rolls from one direction to the other about its long-axis. This rolling action of the body is called bodyroll. Whereas the functions of the bodyroll have been described frequently, the mechanical cause of the bodyroll has not been described. The forces that contribute to bodyroll must have a component in vertical and/or medio-lateral direction, and this component makes little contribution to forward propulsion. An effective use of the buoyant force is expected to reduce the demands on the arms and legs to generate hydrodynamic forces for bodyroll, and hence maximizing propulsion to improve the performance outcome. The purpose of this study was to determine the buoyant torque about the long-axis and its contribution to the bodyroll exhibited during front crawl swimming performed at a distance pace.

METHODS: Bodyroll was defined as the rolling action of the entire body about the principle axis representative of the long-axis of the body. The amplitude of the bodyroll was determined in three steps: First, the instantaneous values of the moment of inertia and angular momentum of the entire body about the long-axis were computed over the stroke cycle. Second, the angular velocity of the bodyroll was determined every instant from the moment of inertia and angular momentum values. Third, the angular velocity of the bodyroll was integrated over the stroke cycle and the peak-to-peak amplitude of the bodyroll was determined for each trial.

After completing a self-motivated warm-up exercises, eleven members of a collegiate men's swim team were asked to perform front crawl stroke at a distance-pace (mean velocity = 1.3 m/s \pm 0.1). Two panning periscopes (Yanai, et al., 1996) were used to record the performances, and the instantaneous position and orientation of each body segment of the swimmers were determined with a DLT-based algorithm.

The 3×3 mass-center inertia matrix (J_{CM}) of the entire body about three orthogonal axes parallel to the global reference system (GRS) and passing through the center of mass of the entire body (CM) was determined with the equation as follows (Haug, 1992):

$$J_{CM} = \sum_{i=1}^{14} \left(A_{i/GRS} J_{Gi}' A_{i/GRS}^T - m_i \left(r_{Gi/CM}^T r_{Gi/CM} I - r_{Gi/CM} r_{Gi/CM}^T \right) \right)$$

where $A_{i/GRS}$ = 3×3 rotation matrix to represent the orientation of the segment i with respect to the GRS

J_{Gi}' = 3×3 diagonal matrix for the principal moment of inertia of segment i

m_i = mass of the segment i

$r_{Gi/CM}$ = position vector pointing from the CM to the center of mass of the segment i

$I = 3 \times 3$ identity matrix

All body segments were assumed to be symmetric about their own long-axes. Consequently, any axes perpendicular to the long-axis could become a principal (transverse) axis of the segment. The principal moment of inertia of each body segment (J_{Gi}) required for the computation were 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 and his colleague (1969) and Hinrichs (1990).

The moment of inertia about the long-axis of the entire body (J_L), that is, the smallest of the three principal moments of inertia, and the long-axis were determined for every given instant as an eigenvalue and the corresponding eigenvector of J_{CM} , respectively.

The angular momentum of each body segment 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 ($I_{Trunk} / 2$). The rotations of the upper and lower halves of the trunk about the long-axis were determined respectively by using shoulder joint-centers and hip joint-centers. The second modification was that the angular velocities the head and limb segments were not assumed to be zero but estimated from the angular velocity of the trunk, in accordance with the method described by Dapena (1997). The angular momentum of the entire body about the long-axis (H_L) was determined as the dot product of the vector representing the long-axis and the angular momentum vector.

The bodyroll was determined as follows:

$$Bodyroll(t) = \int \frac{H_L}{J_L} dt$$

The peak-to-peak amplitude of the bodyroll (BR) was determined for each trial as the difference between the maximum and minimum valued of the *Bodyroll(t)*.

The bodyroll is generated supposedly by the hydrodynamic forces acting eccentrically to the long-axis and the buoyant torque acting on the entire body. The buoyant torque was determined on the basis of the method described by Yanai (1999). In short, this method uses the positions and orientations of all body segments determined by three-dimensional videography and the dimensions of each body segment estimated on the basis of body segment parameters reported in the literature (density and centroid position – Drillis and Contini, 1966; mass – Clauser et al., 1969; position of the center of mass – Hinrichs, 1990). The volume of the torso was estimated as the sum of the volume calculated from the mass and density, and the volume of air in the lungs (lung volume). A lung volume of 4.3 liters, which was estimated from the tidal volume measured during front crawl swimming (2.0 – 2.5 liters reported by Ogita and Tabata, 1992; 2.3 liters reported by Town and Vanness, 1990) and the residual volume of competitive swimmers (1.96 liter Armour, et al., 1993), was used to approximate the average volume of air in the lungs while the subject was swimming. The volume and centroid of the entire body under the water surface were computed numerically for every field. The water surface was assumed to be a sine wave with the wavelength equal to one half of the stature of the subject and the amplitude estimated as a function of swimming velocity. The buoyant torque about the CM was determined for every instant as the cross product of the vector from the CM to the center of buoyancy and the vector representing the buoyancy force. The component of the buoyant torque about the long-axis of the body was determined as the dot product of the buoyant force vector and the vector representing the long-axis.

The angular momentum of entire body that the buoyant torque could generate by itself was computed by integrating itself over the stroke cycle. The angular velocity and the peak-to-peak amplitude of the bodyroll (BR_{BT}) that the buoyant torque could generate by itself were computed with the same method described earlier.

The contribution of the buoyant torque to the bodyroll was determined as the ratio of the BR over the BR_{BT} . The data analysis consisted of the computation of means and confidence intervals (CI) of the variables at 95 % level.

RESULTS: The J_L value changed in the mean range from 0.82 (CI = \pm 0.13) to 1.78 (CI = \pm

0.24) kgm². The change occurred at higher frequency than the stroke frequency (Figure 2). The maximum value was attained in the middle of the recovery phase and the minimum value attained when the front arm was stretching forward after the entry into the water.

The H_L varied in a sinusoidal pattern at the stroke frequency (Figure 2) in the mean range from -3.13 to 3.03 kgm²/s (CI = ± 0.38 kgm²/s). The peak value of the H_L that the body possessed when it was near flat on the water surface was reduced to zero in the first half of the recovery phase. The buoyant torque acted in the direction opposite to the H_L in this period. This period ended nearly coincident with the instants at which the buoyancy torque attained their peak values. In the later half of the recovery phase, the H_L increased in the direction that the buoyancy torque was acting. These observations suggest that the buoyancy torque function to limit the amplitude of the bodyroll by reducing the H_L in the early part of the recovery phase and to initiate the bodyroll toward the other side by generating the H_L .

The angular velocity of the bodyroll ranged from -3.35 to 3.00 (CI = ± 0.42) radians / s, attaining the maximum and minimum velocities when the recovery arm had completely entered into the water and stretched forward. The mean value for the BR was 1.43 (CI = ± 0.17) radians.

The buoyancy torque generally attained its peak value in the middle of the recovery phase, reaching the mean magnitude of 7.7 Nm (CI = ± 1.3 Nm) for both sides (Figure 2). This magnitude of buoyant torque could generate the mean BR_{BT} of 1.26 (CI = ± 0.21 Nm) radians. The mean ratio of the BR over the BR_{BT} was 88% (CI = $\pm 14\%$) for eleven subjects.

DISCUSSION: The purpose of this study was to determine the buoyant torque about the long-axis and its contribution to the bodyroll exhibited during front crawl swimming performed at a distance pace. The results of the present study showed that the buoyancy torque accounted for 88% of the bodyroll for male competitive swimmers performing at a distance pace. This finding indicates clearly that the theoretically favorable source for maintaining bodyroll cycle is, in fact, the primary source of bodyroll used by the competitive swimmers. Hence, it is evident that the demands on the hydrodynamic forces generated by the limb movements for maintaining bodyroll cycle is limited. The results, however, could not support or reject a postulation that an effective use of buoyant force maximizes propulsion and improves the performance outcome. On the assumption that competitive swimmers were likely to have adapted the techniques to swim more efficiently than recreational swimmers, the results might provide a certain degree of support for this postulation. However, further studies are indicated to determine (a) the difference in contribution among swimmers of various skill levels and (b) the relationship between the contribution and the efficiency of swimming, such as physiological energy cost, so that the postulation could be evaluated thoroughly.

The time-course of change in buoyancy torque generally exhibited an inverse relationship with the sinusoidal patterns of change in BR angle. The function of the buoyancy torque on bodyroll is postulated on the basis of this result: The buoyancy torque decelerates the on-going bodyroll until the middle of the recovery phase where the maximum bodyroll is attained, and then initiates the bodyroll toward the other direction.

Limitations of the present study were that various parameters, such as the body segment parameters, lung volume and the amplitude of waves, were not measured directly from the subject, but estimated on the basis of the values reported in literature. The range of error in calculating the moment arm of the buoyant force about the longitudinal axis is expected to be limited for two reasons: First, the error in determining the body segment parameters affects both sides of the body equally, and thus its effects on the computation of the moment arm may well be cancelled out. Second, the air in the lungs is distributed nearly equally to both sides of the body and does not affect the computation of the moment arm of the buoyant force. The effects of the error in estimating the lung volume (± 1 liter) and wave amplitude (\pm

50 %) altered the contribution of buoyancy torque on bodyroll by less than 1 % (87 – 89 %). These results indicate that possible errors in calculating the buoyancy torque about the long-axis are small and the results obtained in the present study were reliable.

CONCLUSION: The findings of this study support the following conclusions:

1. The buoyancy torque acted from one direction to the other, fluctuating synchronously with the stroke cycle and attaining the peak value (mean = 9 Nm) in the middle of the recovery phase.
2. The buoyancy torque was the primary source of bodyroll exhibited by front crawl swimmers performing at distance pace, accounting for 88 % of the bodyroll.
3. The buoyancy torque functioned to decelerate the on-going bodyroll until the middle of the recovery phase where the maximum bodyroll is attained, and then to initiate the bodyroll toward the other direction.

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