Buoyancy is the primary source of generating bodyroll in front-crawl swimming

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Abstract

The present study was conducted to determine the contribution of the turning effect of buoyant force for generating bodyroll and its relationship with the subjects’ variability in swimming speed at distance pace and sub-maximal sprinting pace. The performances of front crawl swimming performed by 11 skilled swimmers were recorded with two panning periscopes for three-dimensional analysis. The bodyroll (BR) exhibited by each of the 11 male competitive swimmers was determined for every given instant as the time-integral of the conceptual angular velocity of the entire body about the long-axis, which was computed from the angular momentum and the moment of inertia of entire body. The part of BR generated by the buoyancy torque (BRBT) was determined from the moment of inertia of the entire body and the double time-integral of the buoyancy torque. The mean value for the peak-to-peak amplitude of the buoyancy torque was 15 Nm at distance pace and 19 Nm at sub-maximum sprinting speed. The contribution of buoyancy to BR was significantly greater ($p<0.01$) than that of the hydrodynamic forces. The individual swimming speed at sub-maximal sprinting pace was positively correlated ($p<0.04$) with the contribution of buoyancy to BR. These results showed that the skilled swimmers used buoyant force as the primary source of generating BR, and that faster swimmers used buoyant force more effectively to generate BR than slower swimmers. Based on the results and subsequent theoretical analysis, possible patterns of arm-BR coordination that may increase the effectiveness of using buoyant force for BR are discussed.

Keywords: Angular momentum; Center of buoyancy; Moment of inertia; Principal axes; Three-dimensional videography

1. Introduction

In front crawl swimming, the swimmer’s trunk undergoes oscillatory rolling motion about the long-axis of the body at the frequency harmonic to the stroke cycle. This rolling action has often been reported as the amplitude of the angular displacement of the trunk (Beekman and Hay, 1988; Levinson, 1987; Liu et al., 1993, and Yanai, 2001b). Swimmers are often advised to increase the amplitude of the trunk roll for improving performance. Counsilman (1968) suggested that trunk roll would (a) make the recovery of the arm easier and permits a shorter radius of rotation of the recovery arm; (b) place the strongest part of the arm pull more directly under the center of mass of the body; (c) place the hips in such a position that the feet can be thrust partly sideways during the kick, thus canceling the sideways-way of the torso possibly created by the forward swing of the recovery arm; and (d) facilitate breathing. More recently, trunk roll was found to contribute to the medio-lateral movements of the hand during the stroke phase (Liu et al., 1993, Payton et al., 1997), which supposedly provides advantages in generating lift by the hands. Furthermore, sports medicine practitioners suggest that an increase in trunk roll reduces the risk of developing shoulder impingement (Ciullo and Stevens, 1989; McMaster, 1986; Neer and Welsh, 1977; Penny and Smith, 1980; and Richardson et al., 1980).

The amplitude and frequency of the trunk roll cycle is determined by several factors: (a) The fluid forces (buoyant and hydrodynamic forces) that generate the rolling action of entire body with respect to an inertial reference system attached to an outside body (e.g. pool deck); (b) the internal forces and torques that generate a rolling of the trunk with respect to the rest of the body; and (c) the moment of inertia of the trunk. Yanai (2001b) investigated the mechanical cause of trunk roll
and found that the turning effect of the fluid forces acting on the entire body was the primary source of the trunk roll. In a subsequent kinematic analysis, Yanai (2003) found that the rolling of the entire body around its long-axis accounts for over 68% of the rolling of the lower trunk (hip roll) and over 50% of the rolling of the upper trunk (shoulder roll), supporting the earlier finding. These findings suggest that the factors influencing the rolling action of the entire body, defined as BR in the present study, are the primary determinants of the trunk roll.

BR is generated by a force component perpendicular to the long-axis of the swimmer's entire body that has little contribution to the forward propulsion. Hence, an effective movement of the arms and legs for generating hydrodynamic forces to drive BR is not likely to be an effective movement for generating propulsion. Rather, the use of an effective technique for generating a large force to drive BR may hinder the swimmer from maximizing propulsion. It seems paradoxical that an increase in BR has been advised to improve performance if adopting a body movement that maximizes the hydrodynamic forces for BR may have the undesirable effect of sacrificing propulsion.

One possible source of torque for generating BR that does not sacrifice propulsion might be the moment of buoyant force around the long-axis of the body. In the recovery phase of front-crawl, the arm on the recovery side is lifted out of the water, not being subject to the buoyant force. The center of buoyancy shifts away from the recovery side and thus a torque is generated (Fig. 1). Theoretically, this torque, named buoyancy torque in the present study, should function to decelerate ongoing BR in the early recovery phase, and initiate BR toward the other direction in the later recovery phase. The use of buoyant force for BR seems to be an effective method for generating BR. In light of these considerations, the present study was conducted to test hypotheses that in front crawl of skilled swimmers, (a) the turning effect of buoyant force is the primary source of generating BR and (b) the greater the contribution of buoyancy to BR a swimmer achieves, the faster the speed the swimmer attains.

2. Methods

Eleven members of a collegiate men’s swimming team (height: 1.83 ± 0.07 m and mass: 77 ± 8.2 kg) participated in this study. After the completion of self-motivated warm-up exercises, each swimmer was asked to perform front-crawl swimming at a distance-pace and a sub-maximum sprinting pace for two lengths of a 22.9 m pool (1.3 ± 0.1 m/s and 1.6 ± 0.1 m/s, respectively). A three-dimensional videography technique with panning periscopes (Yanai et al., 1996) was used to determine the position and orientation of each body segment of the swimmer throughout the stroke cycle. The camcorders fixed to the periscopes (Panasonic AG 450-SVHS) were operated to record at 60 fields per second. The Human Subject Review Committee approved the procedure for data collection and each subject provided written informed consent.

The videotapes of the performances were manually digitized for every field using a Peak 2D System (Peak
Performance Technologies, Denver, CO, USA) for one stroke cycle. Twenty-one body landmarks were digitized in each field to represent the end points of the head, torso, upper arms, forearms, hands, thighs, shanks and feet. The resulting sets of two-dimensional coordinate data were used to determine the corresponding three-dimensional coordinates, and expressed with respect to a global reference system embedded to the pool deck at the water surface. The three-dimensional coordinates were smoothed using a Butterworth digital filter (Winter et al., 1974) with various cut-off frequencies (2–4 Hz) selected to retain at least 95% of the power of the raw signal.

The buoyancy torque was determined with the method described by Yanai (2001a). 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 4.2 l, which was estimated from the tidal volume measured during front crawl swimming (2.0–2.5 l reported by Ogita and Tabata, 1992; 2.3 l reported by Town and Vanness, 1990) and the residual volume of competitive swimmers (1.96 l Armour and Donnelly, 1993), was used to approximate the average volume of air in the lungs while the subject was swimming at a sub-maximal sprinting speed. The volume and centroid of each body segment under the water surface was computed numerically for every field. The water surface was assumed to be a sine wave with the amplitude estimated as a function of swimming velocity and the wavelength equal to the stature of the subject for the sub-maximal sprinting pace and with the wavelength equal to one-half the stature of the subject for the distance pace.

The turning effect of buoyant force about the CM was determined as the sum of the cross products of the vector pointing from the CM to the segmental center of buoyancy and the vector representing the buoyancy force acting on the segment. The component of the turning effect that contributes to BR was used for the analysis. The magnitude of BR generated by the buoyancy torque was determined with a three-step procedure. First, the angular momentum of the entire body that the buoyancy torque could generate by itself (BR_{BT}) was determined by numerically integrating the buoyancy torque vector over the stroke cycle and extracting the component about the long-axis of the body for every field. The initial value of BR_{BT} required for this integration was determined so that the mean value over the stroke cycle for the BR_{BT} equaled that for the H_{WB}. Second, the moment of inertia about the long-axis of the entire body (I_L) was determined for every field with the procedure described by Yanai (2003). The body segment parameters reported in literature (Clauser et al., 1969; Hinrichs, 1990; Whitsett, 1963) were used for this computation. Finally, the H_{BT} was divided by J_L for every field and integrated over the stroke cycle to determine the BR that the buoyancy torque could generate by itself (BR_{BT}). The determined BR_{BT}, 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 when the determined amount of buoyancy torque was applied to it.

The corresponding angular momentum of the entire body and BR that were actually exhibited by each swimmer during the performance were also determined for every field with a procedure as follows: First, the angular momentum of the entire body was determined with the procedure described by Dapena (1978). With this procedure, the angular momentum of the entire body about its CM was computed as the sum of the transfer term and local term of segmental angular momentum measured with respect to a translating reference system attached to the CM of the body. For the computation of the local term for non-trunk segments, the angular velocity vector of each segment was determined as the sum of the angular velocity vector of the line connecting the end points of the segment and the projection of the trunk angular velocity vector on the segmental long-axis (Dapena, 1997). Although the hand and forearm are expected to rotate about their long-axes at a faster velocity than the trunk, their small segmental moment of inertia about the long-axis would make the effect of underestimation in the angular velocity insignificant. Second, the angular momentum of the entire body about its long-axis was divided by the corresponding moment of inertia and integrated over the stroke cycle to determine the BR exhibited by the swimmer. The determined BR, 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. Finally, the difference between the BR and BR_{BT} depicted the BR generated by the hydrodynamic forces (BR_{HD}). Although the three measures of BR (BR, BR_{BT} and BR_{HD}) had only conceptual, but no physical, significance because of a swimming human body not being a single rigid system, computation of these quantities

1 An unrealistic amount of underestimation in the angular velocity of the hand and forearm about their long-axes of over 20 rad/s (=1200°/s) results in an underestimation of the angular momentum of the entire body by 1%. This indicates that an error in estimating the segmental angular velocity about the long-axis makes little influence to the determined angular momentum of the entire body.
made it possible to distinguish the amount of BR generated by two different sources of torque.

The data analysis consisted of the computation of means and confidence intervals (CI) of the variables at 95% level. The contribution of the buoyancy to BR was determined for each trial as the percent ratio of the overlapping area relative to the total area [Contribution = (Overlapping area/Total area)100%]. The contribution of the hydrodynamic forces to BR was determined with the same procedure using the BR_{HD}-time curve and the BR-time curve to determine the overlapping area.

3. Results

The buoyancy torque generally attained its peak value in the middle of the recovery phase (Fig. 3). The mean value for peak-to-peak amplitude of buoyancy torque was significantly different ($p<0.02$) between distance pace (mean = 15.4 Nm) and sub-maximal sprint pace (mean = 18.6 Nm). The BR and BR_{BT} exhibited sinusoidal pattern with phases nearly perfectly matching each other (Fig. 3). For the distance pace, the mean values for peak-to-peak amplitude of BR and BR_{BT} were 1.44 and 1.26 rad, respectively (Table 1). For the sub-max sprinting, the mean values for peak-to-peak amplitude of BR and BR_{BT} were 1.14 and 0.74 rad, respectively (Table 1). The BR_{HD} exhibited a sinusoidal pattern with various frequencies and phases (Figs. 3–5, attaining the mean value for the peak-to-peak amplitude of 0.59 rad for the distance pace and 0.71 rad for the sub-maximal sprinting pace (Table 1).

The contribution of the buoyancy to BR was 75% for the distance pace and 61% for the sub-max sprint pace, whereas the contribution of the hydrodynamic forces to BR was 25% for the distance pace and 39% for the sub-max sprint pace (Table 2). There was a significant difference between the contribution of buoyancy to BR and the contribution of hydrodynamic forces to BR ($p<0.01$) with no interaction effect across the two paces.
contributions and two swimming paces, supporting the first hypothesis. The correlation between the swimming speed and the contribution of buoyancy to BR (Fig. 6) was significantly greater than zero ($p < 0.04$) for the sub-max sprinting pace ($r = 0.64$), supporting the second hypothesis.

### Table 1

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Buoyancy torque (Nm)</th>
<th>BR (rad)</th>
<th>BR$_{BT}$ (rad)</th>
<th>BR$_{HD}$ (rad)</th>
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<tr>
<td></td>
<td>Slow</td>
<td>Fast</td>
<td>Slow</td>
<td>Fast</td>
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<tr>
<td>1</td>
<td>21.0</td>
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<td>1.34</td>
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<td>1.11</td>
<td>1.11</td>
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<td>3</td>
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<td>16.4</td>
<td>1.67</td>
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<tr>
<td>4</td>
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<td>1.58</td>
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<td>1.37</td>
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</tr>
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<td>14.8</td>
<td>1.71</td>
<td>1.44</td>
</tr>
<tr>
<td>7</td>
<td>12.8</td>
<td>17.1</td>
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<td>14.2</td>
<td>1.62</td>
<td>1.36</td>
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<tr>
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<td>12.9</td>
<td>1.58</td>
<td>1.34</td>
</tr>
<tr>
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<td>1.23</td>
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</tr>
<tr>
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<td>13.2</td>
<td>16.8</td>
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</tr>
<tr>
<td>Mean</td>
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<td>1.44</td>
<td>1.14</td>
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<tr>
<td>95% CI</td>
<td>±2.2</td>
<td>±3.4</td>
<td>±0.17</td>
<td>±0.15</td>
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</table>

Fig. 4. A unique pattern of change in the hydrodynamic effect of BR (BR$_{HD}$) exhibited by Subject 1 during the performance at sub-maximal sprinting pace. The value changed in a sinusoidal pattern at the kicking frequency (six-beat technique). Three subjects exhibited this pattern for distance pace and one subject exhibited for sub-maximal sprinting pace.

Fig. 5. A unique pattern of change in the hydrodynamic effect of BR (BR$_{HD}$) exhibited by Subject 1 during the performance at distance pace. Mostly, the hydrodynamic effect of BR is in the opposite direction to the observed BR and the buoyancy effect of BR exceeds the observed BR. This pattern indicates that the hydrodynamic forces have reduced the amplitude of BR that could have been attained hypothetically by the buoyancy torque alone. Thus, the attainment of the observed BR is attributable almost entirely to the buoyancy torque. Three subjects exhibited this pattern for distance pace and no subject exhibited for sub-maximal sprinting pace.

4. Discussion

The present study was conducted to test hypotheses that in front crawl of skilled swimmers, (a) turning effect
of buoyant force is the primary source of generating BR and (b) the greater the contribution of buoyancy to BR a swimmer achieves, the faster the speed the swimmer attains. The results showed (a) that the contribution of buoyancy to BR was greater than the contribution of hydrodynamic forces to BR among the male competitive swimmers performing at distance and sub-maximal sprinting paces and (b) that those swimmers who attained faster speeds used the buoyancy torque more effectively in driving BR than those who attained slower speeds. The former result indicated that the theoretically favorable source for maintaining the BR cycle was, in fact, the primary source of BR used by the competitive swimmers, supporting the first hypothesis. The latter result supported the second hypothesis, suggesting that an effective use of buoyant force might be associated with performance improvement.

The accuracy of the determined contribution of buoyancy to BR depends on the accuracy in determining the whole body angular momentum and the buoyancy torque. The accuracy in the computation of the whole body angular momentum about the long-axis with the present method, namely the Dapena method, was tested in a laboratory setting. A subject standing on a force platform (OR 6-5-1 SN 3171, AMTI, Watertown, MA, USA) performed a front-crawl-like motion as if he was swimming vertically upwards, at two different stroke frequencies (moderate = 0.67 Hz & fast = 1.03 Hz). The force platform measured the resultant forces and torques exerted on the subject during the performance and two Panasonic camcorders recorded the body movements. The angular momentum of the whole body about the vertical axis passing through the center of mass was then determined with two methods, the Dapena method and a forward dynamics method. With the latter method, the resultant forces and torques measured by the force platform and the center of mass positions computed from the video recordings were used to determine the whole body angular momentum about the vertical axis passing through the center of mass. The results showed that the values determined with the two methods matched well. The correlation coefficient between the two sets of angular momentum data for one complete cycle was 0.99 for the two paces. The Dapena method overestimated the peak-to-peak amplitude of the angular momentum about the vertical axis by 0.6 kgm²/s (12%) for the moderate pace and underestimated by 0.3 kgm²/s (4%) for the fast pace. The effects of these errors on the computation of angular displacement of the whole body about the vertical axis (representative of BR) were not substantial. The correlation coefficient between the two sets of BR for one complete cycle was 0.99 for the two paces. The Dapena method resulted in 6% (8%) of overestimation for the peak-to-peak amplitude of BR for moderate pace and 3% (4%) of underestimation for fast pace. The magnitudes and directions of error were consistent across two trials tested for each pace. These results indicate that the error associated with the computation of angular displacement of the whole body about the vertical axis (representative of BR) were not substantial. The correlation coefficient between the two sets of BR for one complete cycle was 0.99 for the two paces. The Dapena method resulted in 6% (8%) of overestimation for the peak-to-peak amplitude of BR for moderate pace and 3% (4%) of underestimation for fast pace. The magnitudes and directions of error were consistent across two trials tested for each pace. These results indicate that the error associated with the computation of angular displacement of the whole body about the vertical axis (representative of BR) were not substantial. 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altered the contribution of buoyancy to BR by less than 1%. These results indicate that possible errors in calculating the buoyancy torque about the long-axis are small and do not alter the main results of the present study.

The magnitude of buoyancy torque increased when the swimmers swam at a faster pace. This increase seems to be attributable to the swimmer’s body “riding high” in the water. The high position of the body causes a lesser part of the body to submerge in water. In fact, the average buoyant force acting on the swimmers was reduced from 91% to 88% of body weight (p<0.01) when they changed their swimming speed from distance pace to sub-maximal sprint pace. The influence of this reduction in the volume of submerged body on the magnitude of buoyancy torque was most notable during the recovery phase in which the BR angle was at, or near, maximal. In this phase, the body segments immersed in water were located away from the recovery arm, and thus the center of buoyancy was located away from the recovery side. The high positioning of the body caused a greater volume of the body in the recovery side to emerge above the water surface, shifting the center of buoyancy even farther away from the recovery side. This increased lateral shift in the center of buoyancy causes the buoyancy torque to increase as seen in the increased peak-to-peak amplitude of buoyancy torque (Table 1).

Despite the increase in the magnitude of buoyancy torque observed at the faster pace, the contribution of buoyancy to BR decreased at that pace. These observations can be interpreted to mean that the tuning effect of hydrodynamic forces about the body’s long-axis has increased in the faster pace swimming and overcome the amount of increase observed in the buoyancy torque. According to the literature (International Center for Aquatic Research (ICAR), 1990a, b, 1991a, b; Schleihaufer et al., 1983), the hydrodynamic forces generated by swimmer’s hands does not only act in the forward direction, but it also acts in the medio-lateral and vertical (or non-propulsive) directions. This observation is consistent across various speeds of swimming. Therefore, swimmer’s intensified effort for faster swimming is expected to increase the hydrodynamic forces in both the forward and the non-propulsive directions. For the observed change in swimming speed (23%, from 1.3 to 1.6 m/s), the component of hydrodynamic forces acting in the forward direction should have increased by approximately 50% (≈1.62/1.32)2 and the correspond-

ing increase in the components of hydrodynamic forces in the non-propulsive should also have increased its turning effect by a similar percentage. This percentage of increase exceeds the amount of change (21%) observed in the magnitude of buoyancy torque, which results in the decrease in the contribution of buoyancy at faster pace swimming. Although the actual increase in the components of the hydrodynamic forces has not been measured in the present study, this theoretical analysis provides a numerical support for the interpretation.

Among the 11 subjects, the faster swimmers used the buoyancy torque to a greater extent in driving BR than the slower swimmers. Interestingly, those who gained a larger contribution of buoyancy to BR did not necessarily generate a large buoyancy torque. In fact, no correlation was found between the peak-to-peak magnitude of buoyancy torque and the contribution of buoyancy to BR (p > 0.22). It indicates that generating a large buoyancy torque does not by itself grant an increase in the contribution of buoyancy torque to BR. Instead, it indicates that faster swimmers have used a given amount of buoyancy torque more effectively to generate a desired amount of BR.

How could the buoyancy torque be used effectively to generate BR in practice? The buoyant force and its moment are dependent on the volume of immersed body, which, in turn, is determined by the resultant force and torque acting on the body. Therefore, both hydrodynamic force and buoyant force and their moment affect the movement of the swimmer’s body (that is, linear and angular acceleration, velocity and position) and, in turn, the affected body movement influences both the buoyant force and hydrodynamic force that would act on the body. In other words, both these forces and the body movements are interdependent with each other. Changing one of the forces and/or its moment, therefore, necessarily alters the other and its moment. A desirable technical improvement might, therefore, be to modify some aspects of stroke technique that increase the contribution of buoyancy to BR while preventing any deteriorating effects on the body’s ability to generate hydrodynamic forces for propulsion. Such modifications of stroke technique might be made by aiming at one or more of the following: (a) initiating the recovery phase earlier by having the elbow leave the water while the hand is still making the final sweep and extending the recovery phase by keeping the elbow above the water while the hand enters the water, so that the angular impulse generated by the buoyancy torque in the extended recovery phase would increase,

\footnote{For a swimmer performing at a constant speed, the resultant propulsive force and the resultant drag force (so-called active drag) acting on the entire body must be equal in magnitude and act in the opposite directions. It has been reported that the magnitude of the active drag acting on a front-crawl swimmer is proportional to the swimming velocity with a power of approximately two (Kolmogorov and Duplischcheva, 1992; Toussaint et al., 1988; van der Vaart et al., 1987). Hence, the increase in the magnitude of the resultant propulsive force associated with the change in swimming speed can be approximated by the ratio of the squared values for the two swimming velocities.}
(b) coordinating the timing of the recovery phase with respect to the BR cycle so that the buoyancy torque could effectively decelerate the on-going BR and to initiate BR toward the other direction in every recovery phase, and (c) coordinating the timing of initial stretch of one arm with the outward sweep of the other arm to reduce the body’s moment of inertia about the long-axis so that a greater amount of BR can be attained for a given angular momentum possessed by the body. All three modifications are concerned with coordination of arm movement, and thus they should be achieved without severely affecting the body’s ability to generate propulsive forces. Further study is necessary to determine the relationship between the coordination of the arms with BR and the contribution of buoyancy to BR, and the relationship between the contribution of buoyancy to BR and the propulsive efficiency, so that an ideal technique for generating BR while maximizing propulsion can be identified.

References


