한국운동역학회지, 2002, 제12권 2호, pp. 393-405
Korean Journal of Sport Biomechanics
2002, Vol. 12, No. 2, pp. 393-405

Weightlessness in Water : Its Unexpected Mechanical Effects on Freestyle Swimming

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ABSTRACT

When our body is immersed in water, we experience weightlessness. The degree of weightlessness that we experience varies depending on the proportion of the body immersed in water, being governed by the relationship between the weight of the body and the buoyant force acting on the body. Human body during the performance of swimming is no exception to these influences. Swimmers body is subject to a time and position dependent force system. Even the magnitude of the buoyant force acting on the swimmers body at every given instant and the corresponding position of the CB change continuously.

The findings of this study support the following conclusions. The buoyancy torque was the primary source of bodyroll exhibited by front crawl swimmers performing at distance pace, accounting for 88 % of the bodyroll. Faster swimmers used buoyancy more effectively to generate bodyroll, partially supporting the postulation that an effective use of buoyancy for bodyroll may reduce the generated hydrodynamic forces to be wasted in non- propulsive directions and maximize forward propulsion.

2002년 10월 1일(화) 접수

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I. Introduction

When our body is immersed in water, we experience weightlessness. The degree of weightlessness that we experience varies depending on the proportion of the body immersed in water, being governed by the relationship between the weight of the body and the buoyant force acting on the body. The Archimedes principle describes the rule that determines the amount of buoyant force acting on a body, as follows:

A body that is partially or totally immersed in a fluid will experience an upward buoyant force that is equal to the weight of the volume of fluid displaced by that body (p 104, Kreighbaum and Barthels, 1996).

It indicates that if a body displaces enough water to create a buoyant force that is equal to or greater than the body weight, the body experiences complete weightlessness and it floats. This demonstrates the buoyancys influence to a bodys floatability. Another influence of buoyancy is the turning effect made on the body. The buoyant force is considered to act through a point called center of buoyancy (CB), which is the geometric center of the volume of water displaced by the body. If CB and the center of mass (CM) of the body are aligned vertically, there is no turning effect caused by the buoyant force. If, however, the two centers are not aligned vertically, the buoyant force generates a turning effect about the CM. The CB of a typical human body is located closer to the head than the CM when the body in the anatomical position floats horizontally on the water surface. This arrangement of the CB and CM generates a torque, causing the legs to sink. This demonstrates the buoyancys influence to a bodys natural ability to maintain its horizontal alignment.

Human body during the performance of swimming is no exception to these influences. Swimmers body is subject to a time and position dependent force system. Even the magnitude of the buoyant force acting on the swimmers body at every given instant and the corresponding position of the CB change continuously. Thus, the bodys floatability and its ability to maintain the horizontal alignment change at every instant. These influences are particularly important in competitive swimming because (a) any deficiency or excess of the influence of buoyant force must be supplemented or cancelled out by the forces actively generated by the swimmer, requiring the swimmer to consume additional energy and (b) these actively generated forces make little contribution to propulsion; for example, a lack of the floatability due to deficiency in buoyant force must be compensated by generating an additional vertical forces by arm and/or leg actions, which makes no contribution to the forward propulsion. It seems to suggest that an effective use of buoyancy might minimize the amount of swimmers effort required to float on the water surface and maintain the bodys horizontal alignment.

In the following two sections, the influences of the buoyant force to the swimmers performing a front crawl stroke are presented to specifically examine the second influence described above.

Ⅱ. Influence of buoyancy in bodys horizontal alignment during freestyle swimming

For a horizontally floating human body in water, the buoyant force acts through a point cranial to the CM of the body, generating a torque that sinks the legs and floats the head. This torque disturbs the horizontal alignment of the body. The effect of buoyancy on a swimmers ability to float horizontally has been reported to influence the fluid resistance force and the physiological energy cost of front crawl swimming (Pendergast et al., 1977; Chatard et al., 1990d). The mechanical explanation for this influence has been postulated as follows (Pendergast, 1977; Chatard et al., 1990a,b,c,d; McArdle et al., 1986; McLean and Hinrichs, 1998; Zamparo, et al., 1996): A swimmer who tends to sink in the static position receives an increased drag when swimming, and the swimmer has to increase the kicking effort necessary to elevate the legs to maintain the horizontal alignment. Consequently, a greater amount of energy is required to overcome the increased drag and/or to maintain strong kicks.

This postulation is developed on the basis of two unverified assumptions: The effect of buoyancy on a swimmer during the front crawl is the same as that in a static floating, and the buoyant force and the hydrodynamic forces generated by kicks are the only sources for the horizontal alignment. A study (Yanai, 2001a) was conducted to determine the rotational effect of buoyant force on the horizontal alignment of the body during front crawl swimming and to re-examine the mechanics of horizontal alignment of the swimmers.

Ⅲ. Methods

After completing a self-motivated warm-up exercises, eleven members of a collegiate mens swim team performed front crawl at a distance-pace (mean velocity = 1.3 m/s ±0.1) and at a submaximum sprinting pace (mean velocity = 1.6 m/s±0.1). Two panning periscopes 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 (Yanai et al., 1996).

The torque due to buoyant force was computed from the kinematics of the body segments exhibited during the performance and their dimensions estimated on the basis of body segment parameters reported in the literature (density and centroid of volume Drillis and Contini, 1966; mass Clauser et al., 1969; and center of mass Hinrichs, 1990). Each limb segment was modeled as frustum of cone and the trunk modeled as three elliptic cylinders. The volume and centroid of the entire body under the water surface were computed numerically for every field. 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 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 buoyant torque was determined as the cross product of the vector pointing from the CM to the center of buoyancy and the vector representing the buoyant force. The component of the buoyant torque that influences horizontal alignment was determined as the dot product of the buoyant force vector and the unit vector representing the transverse-axis of the body projected onto the horizontal plane.

The data analysis consisted of the computation of means and confidence intervals (CI) of the buoyant torque in both static floating and swimming conditions. A repeated-measures t-test was conducted to compare the mean values of the buoyant torque between two conditions.

Ⅳ. Results

The CM fluctuated in the mean range of 23 mm, shifting toward the head during the recovery phase (Figure 1). The CB fluctuated in the mean range of 105 mm, shifting toward the legs at or around the initiation of the recovery phase. This shifting of CB occurred because the

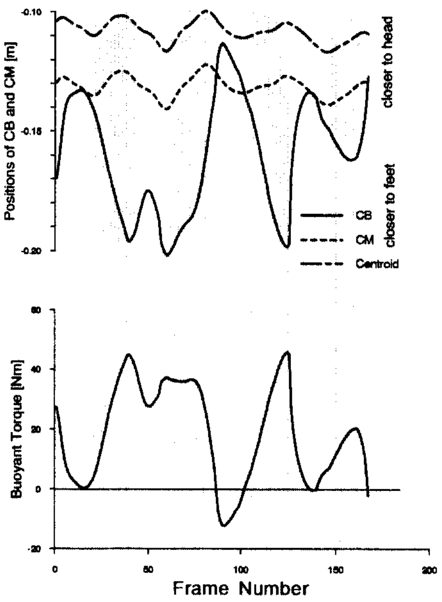


Figure 1.

Volumes of the head, arm and shoulder, all of which were located cranial to the CM, exited out of the water during the recovery phase and were no longer subject to the buoyant force. Due to the different shifting pattern of the two centers, the CM was located cranial to the CB for most of the stroke time. This arrangement of CB and CM generated substantial amount of leg-raising torque was generated for the most of the stroke time (Figure 1). This observation was consistent across all subjects.

The mean effect of buoyancy in static floating condition (6.35 Nm) was to sink the legs, whereas in swimming condition it was to raise the legs and lower the head (22 Nm). The mean leg-sinking effect in static condition was significantly different ($p < 0.05$) from the mean leg-raising effect in swimming condition.

V. Discussion

Limitations of the present study were that various parameters, such as the body segment parameters and the lung volume, were not measured directly, but estimated on the basis of the values reported in literature. Simulations, which introduce the error in estimating inertia parameter by 5 % and lung volume by 2 liters, have shown that the error in these parameters makes small effects on the computations of buoyant torque. The results indicate that a possible error in calculating the buoyant torque is small and the results obtained in the present study are reliable.

The results of the present study demonstrated that the buoyant force generates leg-raising effect. This finding raises a further question: if the buoyant torque acts to raise the legs in front crawl, why do the legs appear to sink during swimming? Figure 2 shows the hydrodynamic forces acting on the hand reported by Schleihauf and the colleague (1983). The resultant fluid force acts eccentric to the center of mass in all three positions, generating counter-clockwise torque. This torque acts in the direction to sink the legs and raise the head. The magnitude of this torque is estimated to be about 25-35 Nm for this subject, which is greater than the mean effect of buoyancy obtained in the present study.

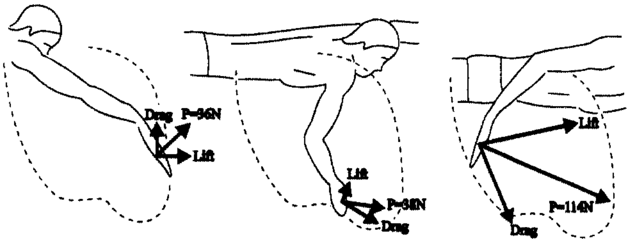


Figure 2.

On the basis of these data, it is postulated that the leg-raising effect of buoyant force, and perhaps of the kick, function to counteract the leg-sinking effect of the hydrodynamic forces acting on the hand, so that the horizontal alignment of the body is maintained during the performance of front crawl.

VI. Conclusion

The present study supports the two findings:

1. Buoyant force generates leg-raising effect during front-crawl swimming; and
2. Buoyant torque functions to counteract the leg-sinking effect of hydrodynamic forces generated by the hand, so that the horizontal alignment of the swimmer was maintained.

Ⅷ. Influence of buoyancy on bodyroll in freestyle swimming

In front crawl, swimmers body undergoes a rolling motion about the long-axis. This rolling of the body, particularly the rolling of the trunk, facilitates the breathing action and helps a smooth arm recovery. This rolling of the trunk is driven by two distinct sources of torques. The first source is the turning effect of external or fluid forces acting on the body. This torque causes the entire body to roll with respect to the global reference frame. The second source is the turning effect of internal forces acting within the body. This torque causes the trunk to roll with respect to the principal axes of the entire body. In this study, the mechanics of this first component of roll that results from external torque was studied. Therefore, bodyroll was defined as the rolling action of the entire body about the longest principal axis of the body.

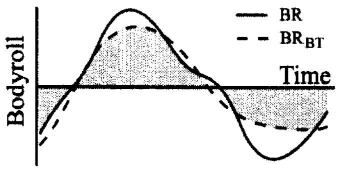
The forces that generate bodyroll must act in vertical or medio-lateral direction, making little contribution to forward propulsion. The buoyant force seems to be an ideal source for bodyroll because it naturally develops and contributes to bodyroll. An effective use of buoyant force may reduce the demands on the arms and legs in generating hydrodynamic forces in non-propulsive directions and maximize forward propulsion. A study (Yanai, 2001b) was conducted to determine the contributions of buoyancy and hydrodynamic forces to bodyroll, and to determine the relations between these contributions and the swimming speed at distance and sub-maximal sprinting paces performed by male competitive swimmers.

Ⅷ. Methods

The same kinematic data obtained from the eleven swimmers for the first part of the study were used for this second study. The bodyroll exhibited by each swimmer was computed with a three-step procedure. First, the angular momentum of the entire body was computed with the procedure described by Dapena (1978). Second, the moment of inertia of the entire body about the long-axis was determined for every field as the smallest eigenvalue of the 3x3 inertia tensor. Finally, the angular velocity of the bodyroll, that is, the angular momentum divided by the moment of inertia, was integrated and the bodyroll was determined as a function of time.

The buoyancy torque was computed with the procedure described in the first part of the study. The bodyroll generated by the buoyancy was determined with a two-step procedure: First, the angular momentum attributable to the buoyancy was computed by integrating the turning effect of buoyancy. Then, the angular velocity of the bodyroll due to buoyancy, that is, the angular momentum divided by the moment of inertia, was integrated and the buoyancy effect of bodyroll was determined. The amount of bodyroll generated by the hydrodynamic forces was determined as the difference between the exhibited bodyroll and the buoyancy effect of bodyroll.

Overlapping area under the two curves



Total area under BR-time curve

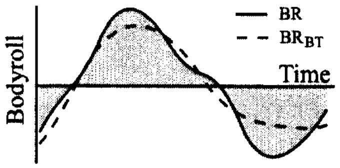


Figure 3.

The peak-to-peak amplitude was determined for the buoyancy effect, the hydrodynamic effect and the exhibited bodyroll. The contributions of the two sources of bodyroll were determined as follows: For buoyancy, the contribution was determined as the fraction of two areas (Figure 3): The numerator of the fraction was the overlapping area under the BR-time curve and the buoyancy effect-time curve, as illustrated in Figure 3, top. The denominator was the total area under the BR-time curve, as indicated in Figure 3, bottom. Because the difference between the two areas depicts the hydrodynamic effect, the contribution of hydrodynamic forces was computed with this formula.

The magnitudes of the two contributions were compared with Analysis of variance. The association between the contributions and swimming speed was examined with correlation analysis.

IX. Results

Figure 4 shows the average values across the subjects for the bodyroll-time curves for one stroke cycle (Top: distance pace, Bottom: sub-max. sprinting). The line with the highest peak presents the exhibited bodyroll, the one in the middle is the buoyancy effect, and the one with the lowest is the hydrodynamic effect. For all subjects, the buoyancy effect was greater than the hydrodynamic effect for both swimming speeds.

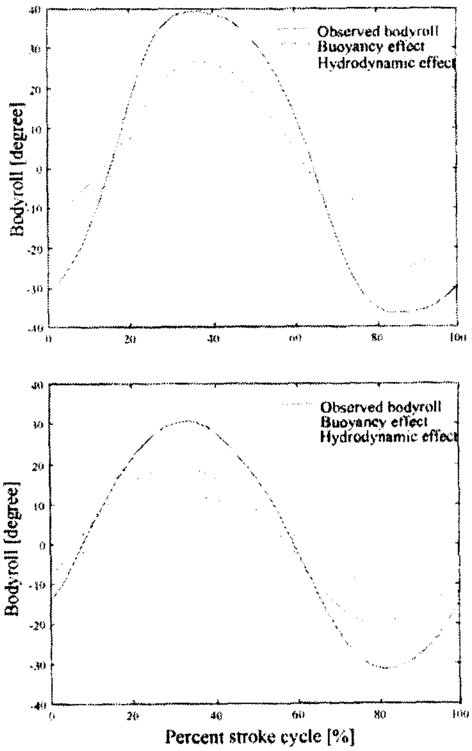


Figure 4.

This observation on the graphs was confirmed statistically. Both the peak-to-peak amplitude and the contribution to bodyroll were significantly greater ($p < 0.05$) for buoyancy effects than the hydrodynamic effects. The results indicate clearly that the buoyancy is the primary source of bodyroll.

Figure 5 shows the correlation between the contribution of buoyancy and swimming speed. Generally, the swimmers who attained fasters swimming speed used buoyancy more extensively to generate bodyroll. The correlation was significant for sub-maximal sprinting.

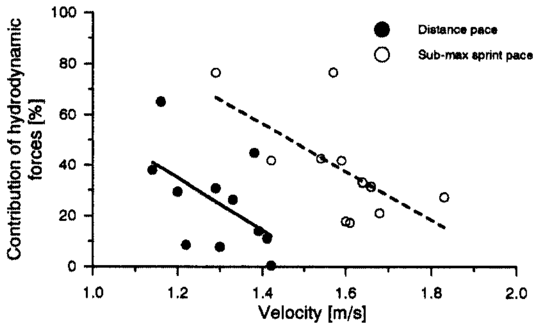


Figure 5.

X. Discussion

There were two major findings from the present study: First finding was that the buoyancy was the major source of bodyroll for male competitive swimmers stroking at both distance and sub-maximal sprinting paces. This finding indicates clearly that the competitive swimmers use the theoretically favorable source for driving bodyroll as the primary source. It also indicates that the competitive swimmers imposed a limited demand on the limbs to generate hydrodynamic forces to drive bodyroll. Second finding was that faster swimmers used buoyancy more effectively to generate bodyroll. This finding provides a certain degree of support to the postulation that an effective use of buoyancy for bodyroll may reduce the generated hydrodynamic forces to be wasted in non-propulsive directions and maximize forward propulsion. 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.

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 litre) and wave amplitude (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.

XI. Conclusion

The findings of this study support the following conclusions:

1. The buoyancy torque was the primary source of bodyroll exhibited by front crawl swimmers performing at distance pace, accounting for 88 % of the bodyroll.
2. Faster swimmers used buoyancy more effectively to generate bodyroll, partially supporting the postulation that an effective use of buoyancy for bodyroll may reduce the generated hydrodynamic forces to be wasted in non-propulsive directions and maximize forward propulsion.

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