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Rotational effect of buoyancy in frontcrawl: does it really cause the legs to sink?

Toshimasa Yanai*

School of Physical Education, University of Otago, PO Box 56, Dunedin, New Zealand

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Abstract

The purposes of this study were to quantify the rotational effect of buoyant force (buoyant torque) during the performance of front crawl and to reexamine the mechanics of horizontal alignment of the swimmers. Three-dimensional videography was used to measure the position and orientation of the body segments of 11 competitive swimmers performing front crawl stroke at a sub-maximum sprinting speed. The dimensions of each body segment were defined mathematically to match the body segment parameters (mass, density, and centroid position) reported in the literature. The buoyant force and torque were computed for every video-field (60 fields/s), assuming that the water surface followed a sine curve along the length of the swimmer. The average buoyant torque over the stroke cycle (mean = 22 N m) was directed to raise the legs and lower the head, primarily because the recovery arm and a part of the head were lifted out of the water and the center of buoyancy shifted toward the feet. This finding contradicts the prevailing speculation that buoyancy only causes the legs to sink throughout the stroke cycle. On the basis of a theoretical analysis of the results, it is postulated that the buoyant torque, and perhaps the forces generated by kicks, function to counteract the torque generated by the hydrodynamic forces acting on the hands, so as to maintain the horizontal alignment of the body in front crawl.

Keywords: Buoyant force; Center of buoyancy; Competitive swimming; Horizontal alignment; Videography

1. Introduction

The human body during the performance of swimming is subject to a time- and position-dependent force system. The magnitude and shape of the submerged volume of the body and the effects of water flow surrounding the body differ for every instant. Through practice, swimmers physically learn how to use this complex force system, so that they can propel their bodies forward in a horizontal alignment. Of all the components of the fluid forces acting on the swimmer's body, the buoyant force is probably the largest and most influential on the horizontal alignment of the swimmer.

For a horizontal aligned human body floating in water, the buoyant force generates a torque about the center of mass of the body which tends to sink the legs and float the head, disturbing the horizontal alignment of the body (Gagnon and Montpetit, 1981; Hay, 1993; Kreighbaum and Barthels, 1996; McLean and Hinrichs, 1998). This effect of buoyancy on an individual's ability to float horizontally was reported to influence the physiological energy cost of front crawl swimming (Pendergast et al., 1977; Chatard et al., 1990d). The mechanical link between the effect of buoyancy and the physiological energy cost has been postulated theoretically (Pendergast et al., 1977; Chatard et al., 1990a–d; McArdle et al., 1986; McLean and Hinrichs, 1998; Zamparo et al., 1996) as follows: A swimmer who tends to sink in the static position receives an increased drag force when swimming and has to increase the kicking effort necessary to elevate the legs to maintain the whole body horizontal alignment. Consequently, a greater amount of energy is required to overcome the increased drag and to maintain strong kicks to keep the horizontal alignment of the body.

This theory implies that the leg-sinking effect of buoyancy and the leg-raising effect of kicks are the primary sources of torques for maintaining horizontal alignment of frontcrawl swimmers. This, however, is based on an

* Tel.: + 64-3-479-8981; fax: + 64-3-479-8309.
E-mail address: tyanai@pooka.otago.ac.nz (T. Yanai).

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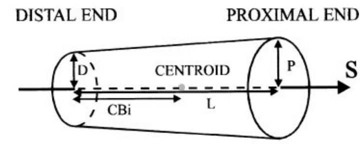
unverified assumption that the effect of buoyancy on a swimmer during the front crawl is the same as that in a static position. Intuitively, this assumption does not seem sensible because the center of mass of the whole body should shift cranially relative to a body landmark (e.g., umbilicus) due to forward movement of the recovery arm whereas the center of buoyancy should shift caudally due to the recovery arm and a part of the head being free from the buoyancy. This difference in the shifting pattern of the two centers might make a substantial change in the rotational effect of the buoyant force during the stroke cycle.

Two hypotheses were formulated on the basis of this theoretical intuition: The buoyant torque that tends to lower the legs and raise the head of the swimmer is lesser during a front crawl swimming than during a static floating, and the buoyant torque does not always act in the same direction during front crawl swimming. The outcome of the present study is expected to provide a firm basis for reexamining the mechanics of horizontal alignment of the swimmers during the performance of front crawl.

2. Methods

Direct measurement of the buoyant torque during the performance of front crawl is nearly an impossible task. An alternative approach was used in the present study in which the buoyant torque was estimated from a swimmer's body dimensions and body configurations exhibited during front crawl swimming. Each body segment was modeled on the basis of available information on body segment parameters (density and centroid of volume[1] — Drillis and Contini, 1966; mass — Clauser et al., 1969; and center of mass — Hinrichs, 1990), and the body configurations of each swimmer exhibited during front crawl and the segment lengths were determined with three-dimensional videography (Yanai et al., 1996).

The subject's body was modeled as a linkage of 16 rigid segments that consisted of head, torso (upper, middle and lower portions), upper arms, forearms, hands, thighs, shanks and feet. The head was modeled as an ellipsoid and each limb segment modeled as the frustum of a cone. The mass and density of each segment were used to determine the volume of the segment. Segment densities reported by Drillis and Contini (1966) were adjusted by multiplying a constant to match the whole body density of competitive swimmers,[2] assuming that the segment



$$volume = \pi \int_0^L \left(\frac{P-D}{L}S + D\right)^2 dS = \frac{mass}{density}$$

$$centroid(CB_i) = \frac{\pi \int_0^L \left(\frac{P-D}{L}S + D\right)^2 S\,dS}{volume}$$

Hence,

$$P, D = f(mass, density, centroid, L)$$

Fig. 1. The model of the limb segment. The radius of each end of the frustum was defined so that the centroid of the frustrum with a given volume matched the literature value of the centroid of the body segment. The length of each segment determined from the video recordings involved the mean measurement error of $< 3\%$.

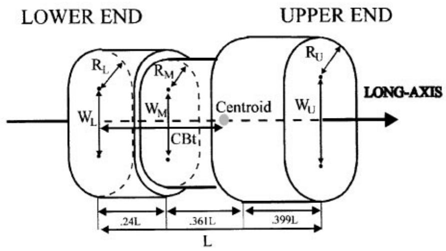
densities are proportional to whole body density. The radius of each end of the frustum was defined so that the centroid of the frustrum with a given volume matched the literature value of the centroid of the body segment (Fig. 1).

The torso was modeled as three cylinders of stadium-shaped cross-section, connected by a pin along the longitudinal axis of the torso (Fig. 2). The lengths of the three portions were defined on the basis of the values reported by de Leva (1996). The sum of the volume calculated from the mass and scaled density, and the volume of air in the lungs (lung volume) determined the volume of the entire torso. The centroid of the torso, excluding the air in the lungs, was assumed to be located at the mid-point between the chin–neck intersect and the mid-point between hip joint centers (mid-hip), which corresponded to 57.8% of the length of the torso from the mid-hip in accordance with the method described by Hinrichs (1990).

The lungs of the torso model were located in the middle of the mixed volume of the upper and middle portions (62% of the torso length from the hip joint centers). A lung volume of 4.2 l was used to approximate the average volume of air in the lungs while the subject was swimming at a sub-maximum sprinting speed. This lung volume 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 by Town and Vanness, 1990) and the residual volume of competitive swimmers (1.96 l Armour and Donnelly, 1993).

[1] Drillis and Contini measured the centroid position of the segmental volume in order to approximate the segmental center of mass. Hence the center-of-mass positions reported in their study are not the 'true' positions of the center of mass, but the positions of the segmental centroid of the volume.

[2] Male competitive swimmers are generally slim and lean [10.4–14.3% body fat (Flynn et al., 1990; McLean and Hinrichs, 1998; Siders et al., 1991; Thorland et al., 1983)]. Whole body density of the male competitive swimmers of this range of body fat was estimated to be $1070\,kg/m^3$, on the basis of the Siri equation (Siri, 1956).



$$volume = \frac{mass}{density} + lung\ volume$$

$$= .24L(R_L{}^2\pi + 2W_LR_L) + .361L(R_M{}^2\pi + 2W_MR_M) + .399L(R_U{}^2\pi + 2W_UR_U)$$

$$= Volume_L + Volume_M + Volume_U$$

$$centroid_{air-inhaled}(CB_t) = \frac{.12L \times Volume_L + .4205L \times Volume_M + .8005L \times Volume_U}{volume}$$

$$= \frac{0.578 \times {}^{mass}\!/_{density} + 0.62 \times lung\ volume}{volume}$$

RL = *radius of proximal end of thigh*

WL = *distance between the hip joint centers*

$2RU + WL$ = *distance between the shoulder joint centers*

Hence,

R_M & R_U = *f (mass, density, centroid*$_{air-inhaled}$*, L, Lung Volume, radius of proximal and of thigh, distance between hip joint centers, distance between the shoulder joint centers)*

Fig. 2. The model of the torso segment. The torso model consisted of three cylinders of stadium-shaped cross-section. The relative lengths of the three portions were determined on the basis of the data reported by de Leva (1996). The transverse lengths, defined as $2R + W$, of the upper, lower and middle portions were defined, respectively, as the distance between the shoulder joint centers, the sum of the distance between the hip joint centers and the diameter of the proximal end of thigh, and 80% of that of the lower torso. The frontal length, defined as $2R$, of the upper and middle portions were then determined to give the required volume and centroid of the entire torso.

Two panning periscope systems (Yanai et al., 1996) were used to record the body configurations exhibited during the performance of front crawl. After having provided written informed consent, 11 members of a collegiate men's swimming team (mean height = 1.83 ± 0.07 m and mean mass = 77 ± 8.2 kg) performed frontcrawl at a sub-maximum sprinting pace for two lengths of a 22.9 m pool (mean value for average speed = 1.6 ± 0.1 m/s).

A global reference system (O: x, y, z) was defined by the x-axis perpendicular to the swimming direction pointing from the left to the right of the subject, the y-axis pointing in the swimming direction, and the z-axis pointing vertically upward. The origin 'O' of the global reference system was located at the surface of the water.

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 two consecutive stroke cycles. In each digitized field, 21 body landmarks were visualized and digitized to represent the end points of each body segment. Some difficulties were encountered in the visualization of body landmarks when some body segments were obscured by others. Such difficulties generally occurred in four or five consecutive fields. The operator carefully observed the body movements for several fields before and after the obscured section and estimated the positions of the body landmarks in that section (the digitize-redigitize reliability was high [$r > 0.98$]). The resulting sets of two-dimensional coordinate data were transformed into three-dimensional coordinates with a DLT-based algorithm (Yanai et al., 1996), and expressed with respect to the global reference system. The three-dimensional coordinates were then smoothed using a second-order, low-pass, recursive Butterworth digital filter (Winter et al., 1974).

The "two-waves" pattern (Fig. 3) described by Firby (1975) was observed for the subjects in the present study. The wave pattern was approximated as a sine wave with the wavelength equal to the stature of the subject and the highest points attained at the vertex and the heel of the subject. The amplitude of the waves was estimated for each subject on the basis of swimming velocity. Takamoto et al. (1985) reported that the wave power (the mean sum of squares of instantaneous wave height) for elite front crawl swimmers could be expressed as a function of swimming velocity as follows:

$$\text{Wave power} = \frac{1}{T}\int_{t}^{t_1+T} h(t)^2\, dt = 6.04 * \text{velocity}^{1.94}$$

$$(r = 0.83, n = 51),$$

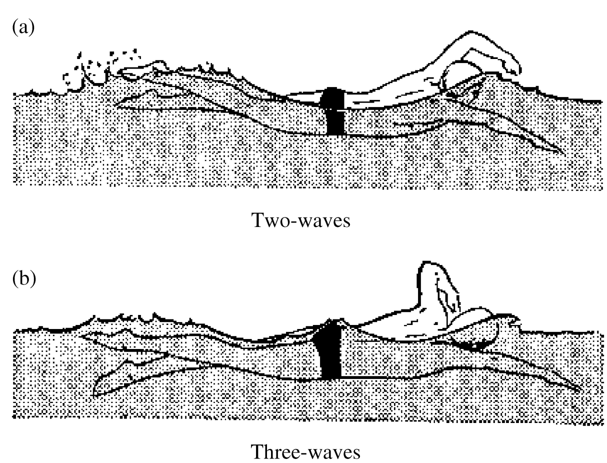


Fig. 3. Two wave patterns described by Firby (1975). Cited from *Howard Firby on Swimming,* Firby, H., Pelham Books: London. Firby stated that "two-wave freestylers" are usually sprinters who use an "arched-back, busy-kick style" of front crawl technique whereas "three-wave freestylers" are those "who tend toward the head-lowered, body-stretched-out, subdued type of swimming seen more in distance events."

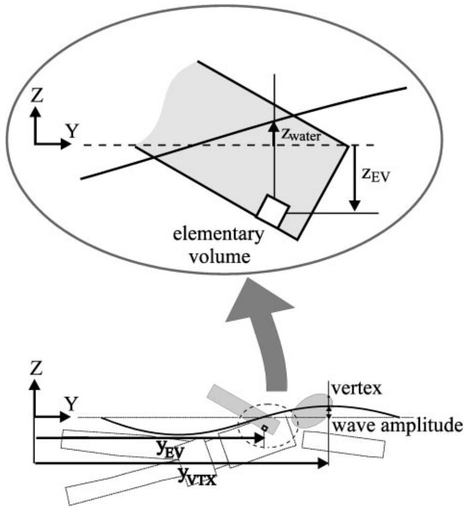


Fig. 4. Schematic presentation of the method of identifying the elementary volumes of body located under water surface. An elementary volume was considered to be submerged in water if its z-coordinate (z_{EV}) was equal to or less than the z-coordinate of the water surface directly above, or below, the elementary volume (z_{water}). The z_{water} was determined with the equation presented in the text for every elementary volume for every given instant.

where T is the period during which the measurements were taken ($T = 10\,s$), $h(t)$ the height of water surface relative to the height of still water (cm), and the swimming velocity (m/s). The amplitude of the distinct wave pattern for a given trial was estimated as the square root of the wave power determined for the average horizontal velocity of the trial.

Each segment model was divided into slices of 1–2 mm thickness along the long-axis and each slice sectioned into cuboid-shaped elementary volumes of approximately 5 mm^3. A given elementary volume was considered to be submerged in water if its z-coordinate was equal to or less than the z-coordinate of the water surface directly above, or below, the elementary volume (Fig. 4). The z-coordinate of the water surface (z_{water}) was determined for every elementary volume for every given instant as follows:

$$z_{water} = \text{Wave amplitude} \cos\left[\frac{2\pi(y_{EV} - y_{VTX})}{\text{Wavelength}}\right],$$

where y_{EV} is the y-coordinate of the elementary volume and y_{VTX} the y-coordinate of the vertex. The sum of the elementary volumes located under the water surface determined the total volume of the body in water at that instant.[3] The product of the total volume and the specific weight of the water (9790 N/m^3) determined the buoyant force acting on the whole body. The position vector of the center of buoyancy of the body (CB) was determined as the average point of the first moments of all the elementary volumes located under the water surface about the origin 'O' of the global reference system. The whole body center of mass (CM) was determined for every instant by using the segmental method described by Hay (1993). Finally, the buoyant torque was determined as the cross product of the vector from the CM to the CB and the vector representing the buoyant force. The component of the buoyant torque parallel to the x-axis, which influences the horizontal alignment of the body, was used for analysis.

To determine the buoyant torque in the static condition, the body model representative of each subject was configured mathematically into the horizontally horizontal aligned position. The water surface level relative to the body was altered mathematically until the buoyant force equaled the weight of the subject. The positions of the CB and CM were then determined to compute the buoyant torque.

The descriptive data analysis comprised the computation of mean and confidence interval (CI) at 95% level. A repeated-measures t-test was conducted to determine if the average buoyant torque over the stroke cycle was significantly different from the buoyant torque acting in the static floating condition. A one-sample t-test was used to determine if the mean value across subjects for the maximum leg-raising buoyant torque acted during the performance was greater than zero. The level of significance was set at 0.05.

3. Results

The buoyant torque in the static floating condition acted in the direction to lower the legs and raise the head (Table 1). The mean value for this leg-sinking torque (6.35 N m) was significantly different from zero ($p < 0.01$).

The mean value across subjects for the average buoyant torque acting over two-stroke cycles was directed to raise the legs and lower the head. The mean value (22 N m) was significantly different from zero ($p < 0.01$). This observation was found consistently across the 11 subjects (Table 1). The buoyant torque acting over the stroke cycles was significantly different from the buoyant toque in the static floating condition ($p < 0.01$).

The maximum leg-raising torque (mean = 56 N m) was attained at or around the arm entry into the water, and the maximum leg-sinking torque (mean = 5 N m) attained while both arms were stroking in water. The maximum leg-raising torque was significantly greater than zero ($p < 0.01$) whereas the maximum leg-sinking torque was not, indicating that the buoyant torque acted primarily in the direction to raise the legs and lower the head.

[3] The compounding accumulation error was found to be $< 0.15\%$ for the computation of segmental volume, $< 0.29\%$ of segmental length for the computation of segmental centroid, and $< 0.007\%$ of stature for the computation of the CB of entire body.

Table 1
The buoyant torques (N m) acting on the 11 subjects in static floating condition and during front crawl[a]

	Static floating	Swimming		
		Average	Minimum	Maximum
S1	− 6.97	18.8	− 12.3	45.9
S2	− 11.67	60.8	39.4	86.1
S3	− 5.14	22.4	− 7.4	59.1
S4	− 4.86	27.7	− 10.1	76.5
S5	− 8.18	18.7	− 8.9	64.6
S6	− 5.6	18.4	− 11.0	63.6
S7	− 5.34	19.1	− 9.6	63.2
S8	− 8.21	16.5	− 9.3	35.1
S9	− 5.33	16.4	− 10.7	58.2
S10	− 3.46	12.1	− 9.3	39.1
S11	− 5.06	16.1	− 0.9	29.4
Mean (95% CI)	− 6.35 (− 7.83 ~ − 4.87)	22.4 (13.5 ~ 31.4)	− 4.6 (− 14.5 ~ 5.4)	56.4 (44.7 ~ 68.2)

[a]The negative values indicate the torque that lowers the legs and raise the head.
The buoyant torque acting on the S2 was directed to sink the head and raise the feet throughout the stroke cycle. The swimming velocity of the S2 (1.80 m/s) was the fastest of all, and the body was positioned "higher" on the water surface than the other swimmers. A fairly large volume of the body (head and upper torso) appeared above the water surface at all times, causing the buoyant torque to act in the direction to raise the legs CB and sink the head throughout the stroke cycle.

The positions of the CM and CB fluctuated in the mean range of 23 mm (1.3% stature) and 105 mm (5.8% stature) with respect to the torso, respectively. The CM shifted cranially during the recovery phases while the CB shifted caudally (Fig. 5). The body segments (primarily the head and the recovery arm) located above the water surface and not subject to buoyancy resulted in this large caudal shift of CB, causing to generate the leg-raising torque (Fig. 5).

4. Discussion

The buoyant torque determined in the present study provides as a basis for reexamining the mechanics of the horizontal alignment of swimmers during the performance of front crawl. There are two major findings on the effects of buoyancy among male collegiate competitive swimmers: (a) The buoyant torque measured in a static floating condition was not representative of the buoyant torque acting during the performance of front crawl; and (b) The buoyant torque acted primarily in the direction to raise the legs and lower the head during front crawl. This latter finding contradicts the long-standing notion that one of the functions of kicking is to counteract the leg-sinking effect of the buoyancy. This contradiction jeopardizes the theory that the sinking tendency of a swimmer's legs in static position increases the physiological energy cost of swimming.

The major limitation of the present study was that various parameters, such as the body segment dimensions, lung volume and the amplitude of waves, were not measured directly from the subjects, but estimated on the basis of the values reported in literature. The validity of the measurement of the buoyant torque during the performance of swimming could not be assessed because of the practical difficulty in the measurement of actual values. Instead, the reliability of the main result was tested using various sensitivity tests with simulations and comparing determined values with corresponding values in the literature.

The CB and CM positions, and the distance between them, computed for the models of 11 subjects completely or partially immersed in water were compared with corresponding values for 40 male competitive swimmers measured by McLean and Hinrichs (1995, 1998) and 14 male collegiate physical education students measured by Gagnon and Montpetit (1981). The computed values with the models closely matched the values reported in the two studies in all conditions (Tables 2 and 3). The results suggest that the human body model represent well the distributions of mass and volume across the body segments of the sample population.

The geometric shape of each segment model was defined somewhat arbitrarily and was expected to cause a systematic error in determining the volume and centroid of the segment partially immersed in water. The limb segments were partially immersed in only a few frames in the stroke cycle, which was expected to have minimal effect. The torso was partially immersed most of the time, and thus the shape of the torso model was expected to have substantial effects on the buoyant torque value. Such effects were estimated by adapting various shapes of torso model with the required volume and centroid position in the computation of buoyant torque during the performance. The results (Table 4)

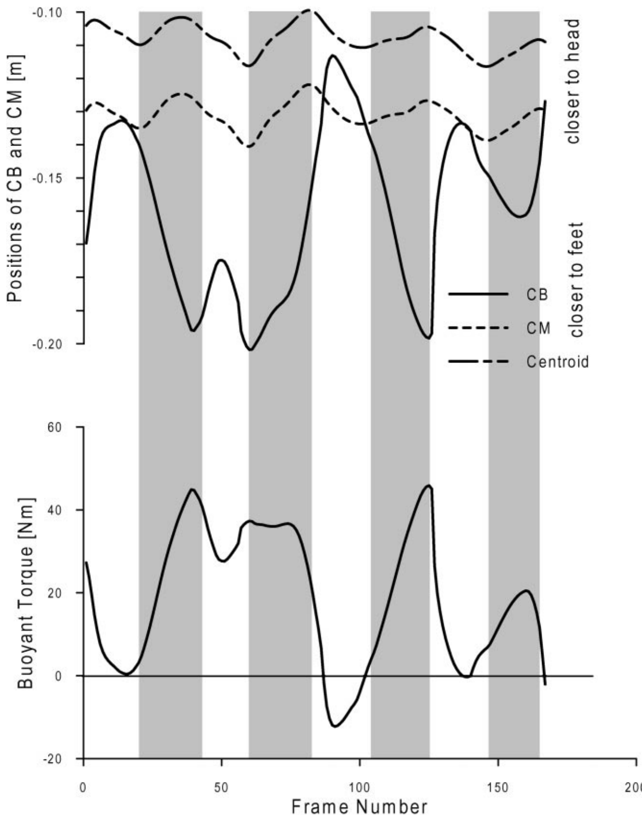


Fig. 5. Typical pattern of change in the positions of the CM, CB and the geometric center (centroid) of the whole body volume (top) and the buoyant torque (bottom) for two-stroke cycles exhibited by majority of subjects. The positions of the CM, CB and the centroid were measured with respect to the geometric center of the torso. The difference between the centroid and CB illustrates the effect of the body segments located above the water surface and not subject to buoyancy on the position of CB. The graph indicates clearly that having body segments (primarily the head and the recovery arm) above water surface has caused the CB to shift caudally and resulted in generating the leg-raising torque. Positive torque values indicate rotational effect that lowers the head and raises the legs. The gray vertical bands indicate recovery phases (the subject took a breath in the second recovery phase).

Table 2
Positions of CB and CM (% stature) in horizontal aligned position[a]

	No-inhalation		Full-inhalation		
	CB	d	CB	d	CM
Present study (submerged)	60.7	0.3	61.5	1.1	60.4
Present study (floating)	—	—	60.9	0.45	60.4
Gagnon and Montpetit	60.4	0.3	—	—	60.1
	60.6[b]	0.3[b]	61.4[b]	1.1[b]	60.3[b]
McLean and Hinrichs	—	—	61.68[c]	0.44[c]	61.24[c]
	—	—	—	1.0[d]	—

[a]In the present study, the lung volumes were assumed to be 2 and 9.2 l for no-inhalation (residual volume) and full-inhalation, respectively (Armour and Donnelly, 1993).The data reported by Gagnon and Montpetit (1981) were the mean values for 14 male collegiate students completely immersed in water.

[b]The mean of two subjects who underwent the experiment for the analysis of breathing state.

[c]The data reported by McLean and Hinrichs (1998) were the mean values obtained from 15 male collegiate swimmers floating horizontally on the water surface.

[d]The mean value obtained from 25 collegiate and master swimmers completely immersed in water (1995).

Table 3
Positions of CB and CM (% stature) in anatomical position[a]

	No-inhalation		Full-inhalation		
	CB	d	CB	d	CM
Present study	57.2	0.6	58.2	1.6	56.6
Gagnon and Montpetit	56.6	0.5	—	—	56.2
	56.5[b]	0.5[b]	57.5[b]	1.5[b]	56.0[b]

[a]In the present study, the lung volumes were assumed to be 2 and 9.2 l for no-inhalation (residual volume) and full-inhalation, respectively (Armour and Donnelly, 1993). The data reported by Gagnon and Montpetit (1981) were the mean values for 14 male collegiate students completely immersed in water.

[b]The mean of two subjects who underwent the experiment for the analysis of breathing state.

indicate that the shape of torso model affects the buoyant torque computed for the stroke cycles to a certain degree (the mean value ranging from 17 to 22 N m) but it does not alter the main result of the present study.

The standard deviation of the mean lung volume of all subjects in this study was approximately 1.0 l, which consists of the standard deviations of 0.3 l (Armour and Donnelly, 1993) for residual volume and $0.1 \sim 0.6$ l (Ogita and Tabata, 1992; Town and Vanness, 1990) for tidal volume. This range of variation in the lung volume results in only a variation less than 1 N m in estimated buoyant torque over the stroke cycle (Fig. 6), which does not seem to be significant.

The effect of the error in estimating the wave amplitude was determined by computing the buoyant torque with altered wave amplitudes ($\pm 50\%$). This range of wave amplitudes resulted in the average position of the vertex of all subjects, including those whose vertex was submerged except during the breathing time ($n = 3$), to locate above the water surface, and that of all subjects, except those whose vertex was located above the water surface for most of the stroke time ($n = 3$), to be submerged under the water surface. The range of wave amplitudes should, therefore, enclose the 'true' amplitude of the wave that the swimmer encountered during the trial. The buoyant torque was affected by ± 3.5 N m (Fig. 7). The change in the buoyant torque due to substituting "three-waves" (Fig. 3) for "two-waves" with the same range of wave heights was less than 3 N m.

Whereas this range of systematic error in the computation of the buoyant torque might still lead to a question on the validity of the model, it does not alter the main finding that the buoyant torque is directed to lower the

Table 4
The effects of various shapes of torso model on the buoyant torque acting during front crawl

	Average	Minimum	Maximum
Present model	22.4 (± 8.95)[a]	− 4.6 (± 10.11)	56.4 (± 11.74)
Two circular cylinders	19.8 (± 8.67)	− 4.7 (± 9.43)	53.0 (± 11.38)
Two elliptic cylinders	17.1 (± 7.82)	− 6.5 (± 7.81)	47.8 (± 10.60)
Two rectangular cylinders	20.4 (± 8.66)	− 4.4 (± 9.38)	52.5 (± 11.10)

[a]The values in parentheses indicate the confidence interval at 95% level.

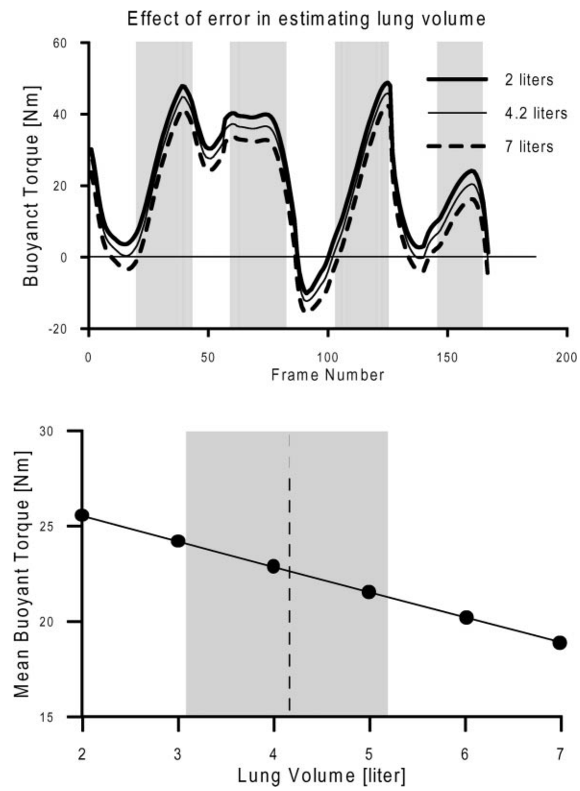


Fig. 6. (Top) The effect of error in estimating the lung volume on the pattern of change in buoyant torque for two stroke cycles exhibited by one subject. (Bottom) The mean effects of error in estimating lung volumes on the buoyant torque. The mean effects were computed as the mean values across the 11 subjects for the average buoyant torque determined over two-stroke cycles. Positive values for the buoyant torque indicates rotational effect that lowers the head and raises the legs. The gray vertical bands indicate the expected range of individual variability in lung volume during the performance of front crawl.

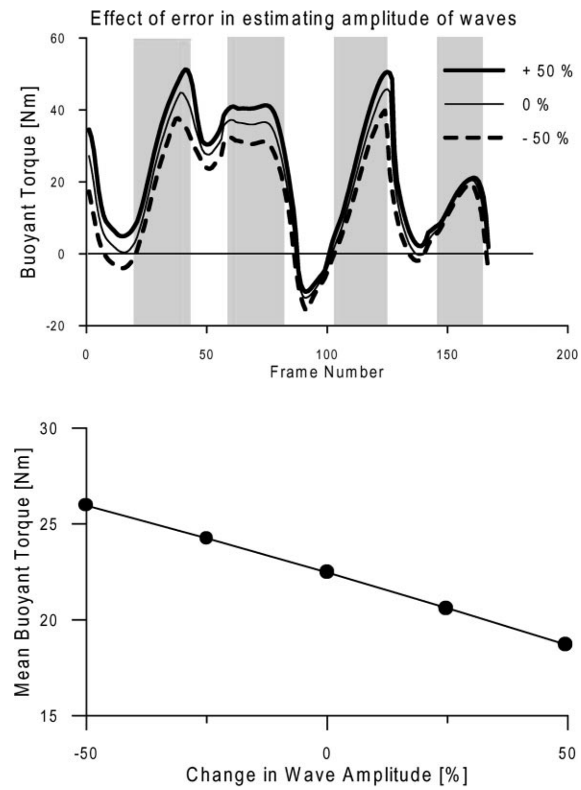


Fig. 7. (Top) The effect of error in estimating the amplitude of waves on the pattern of change in buoyant torque for two-stroke cycles exhibited by one subject. For this subject, ± 50% of change in wave amplitude resulted in the peak-to-peak amplitudes to alter in the range from 44 to 133 mm. (Bottom) The mean effects of error in estimating the amplitude of waves on the buoyant torque. The mean effects were computed as the mean values across the 11 subjects for the average buoyant torque determined over two-stroke cycles. Positive values for the buoyant torque indicates rotational effect that lowers the head and raises the legs.

head and raise the legs during front crawl. It indicates that the main result of the study is reliable and that the degree of approximation in the construction of the model is appropriate for the present purpose of the study.

The finding of this study raises a further question: If the buoyant torque acts to raise the legs and lower the head during front crawl swimming, why do the legs appear to sink during swimming? The hydrodynamic forces acting on the hands might generate a leg-sinking torque. When a swimmer is viewed from the swimmer's right side, the hands rotate about the center of mass of the body in clockwise direction. The drag acts on the hand in the direction opposite to the direction of hand movement, and thus, generates a counter-clockwise torque about the center of mass. This torque acts in the direction that raises the head and lowers the legs. According to the data presented by Schleihauf et al. (1983), both drag and lift acted on the hand to generate counter-

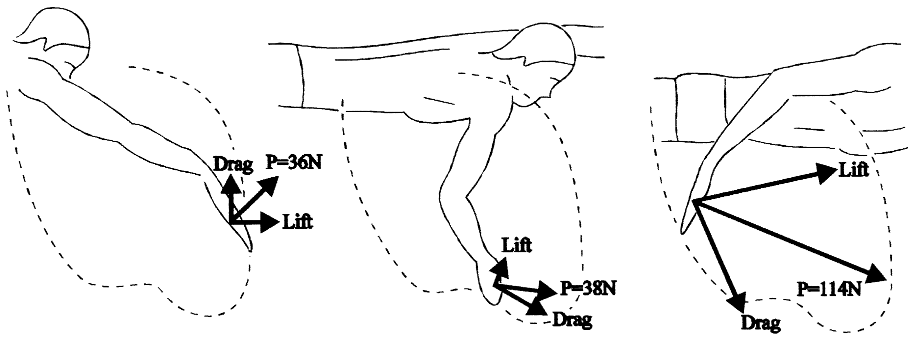


Fig. 8. Hydrodynamic force acting on hand during the performance of front crawl of one subject (Reproduced with permission from the three-dimensional analysis of hand propulsion in the sprint front crawl stroke, in *Biomechanics and Medicine in Swimming*, Human Kinetics. 1983). The resultant forces acting on the hand at the three instants generate counter-clockwise (leg-sinking) torque about the center of mass of the swimmer. Note that the lift and drag do not appear to act perpendicularly in the figure. This is, presumably, an effect of an oblique projection of the three-dimensional vectors (lift and drag) into a two-dimensional plane.

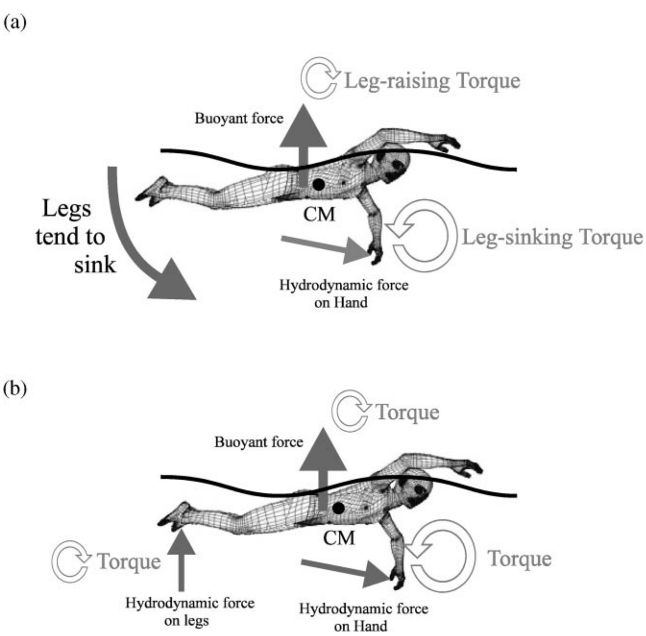


Fig. 9. A postulated mechanism of torque that tends to sink the legs during the performance of front crawl (a) and a function of buoyant torque and kicks (b). The counter-clockwise (leg-sinking) torque generated by the hydrodynamic force acting on hands may overcome the clockwise (leg-raising) torque generated by the buoyant force, causing the legs to sink. The clockwise (leg-raising) torque generated by kicks is expected to work together with the buoyant torque and counteracts the hand-force-driven-torque.

clockwise torques about the CM during front crawl sprinting (Fig. 8). The swimmer in Fig. 6 generated the hydrodynamic force of 36 N in the middle of downward pull. The moment arm of this force about the CM seems greater than the arm length, and thus this force generates a substantial amount of rotational effect on the body (estimated to be about 25–35 N m). The hydrodynamic forces acting on the hand in the middle of backward and upward pulls (38 and 114 N, respectively) might generate similar amounts of rotation on the body. In all three instances, the hydrodynamic forces acted on the hand to generate counter-clockwise torques about the CM. Thus, the reason for the body not adopting the head down alignment in front crawl seems to be the leg-sinking torque generated by the hydrodynamic forces that act on the hands. Hence, it is postulated that the buoyant torque, and perhaps the kick, function to counteract the torque generated by the hydrodynamic forces acting on the hands, so that the horizontal alignment of the body is maintained during the performance of front crawl (Fig. 9). Further study is indicated to examine the validity of this postulation.

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