# A METHOD TO DETERMINE THE MOMENT OF BUOYANT FORCE ACTING ON FRONT-CRAWL SWIMMERS

Toshimasa Yanai
School of Physical Education, University of Otago, Dunedin, New Zealand

The purpose of this study was to develop a method to determine the moment of buoyant force acting on a front-crawl swimmer about the longitudinal-axis (buoyancy torque). The buoyancy torque was determined using three-dimensional kinematic data of one swimming trial and the dimensions of the body segments. Each body segment was modelled as a frustrum of cone, whose dimension matched the body segment parameters (relative mass, density, and centroid) reported in the literature. The buoyancy torque was found to attain its peak value (13 Nm) in the middle of the recovery phase. Sensitivity tests revealed that the individual variability in the body segment parameters would make small effects (< 3 %) on the buoyancy torque. With this method, the effect of buoyant force on body-roll can be determined to a known degree of accuracy.

KEY WORDS: body-roll, density, centre of buoyancy, frustrum of cone, sensitivity analysis

INTRODUCTION: In front-crawl swimming, the body rolls about its longitudinal-axis (body-roll), oscillating from one direction to the other for every stroke cycle. One study investigated the mechanical cause of body-roll and found that the roll was mainly driven by the external torque acting on the swimmer's body, rather than the torque generated by the interactions of the body segments (Yanai, 1998). It was speculated in the same study that the buoyant force acting eccentric to the centre of mass of the body (Figure 1) generated a major source of the external torque. The purpose of the present study was to develop a method to determine the moment of buoyant force acting on a front-crawl swimmer about the longitudinal-axis (buoyancy torque).

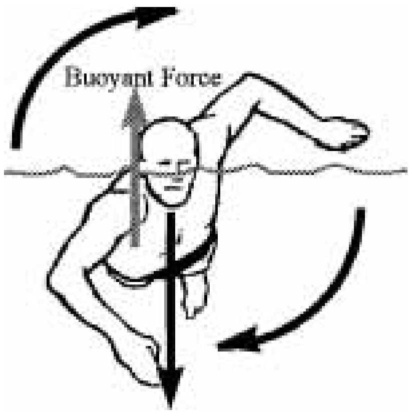


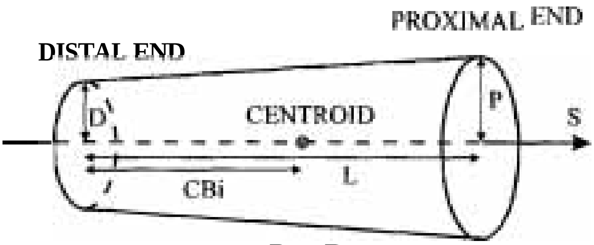

**Figure 1 - Buoyancy Torque**

METHODS: The buoyancy torque acting on a swimmer is dependent on the volume and the centroid of the body immersed in the water, the position of the centre of mass of the body, and the specific weight (density x acceleration due to gravity) of the water. The first two variables were determined by measuring the position and estimating the dimension of each body segment.

A three-dimensional videography technique (Yanai et al., 1996) was used to determine the position of each body segment of a male collegiate swimmer performing front-crawl swimming. Two panning periscope systems were fixed on the pool deck, so that oblique front and back views of the subject were recorded. Panasonic SVHS camcorders were mounted on each of the two periscopes and used to record the performance at the sampling frequency of 60 Hz. The operator panned each periscope system, so that the subject was recorded in the middle of the recorded images throughout the trial. A test section was calibrated to enclose the volume through which the subject performed two consecutive stroke cycles. A global reference system (x,y,z) was defined with the x-axis perpendicular to the swimming direction on the horizontal plane and pointing to the right side of the subject, the y-axis parallel to the swimming direction on the horizontal plane pointing in the swimming direction, and the z-axis pointing vertically upward.

The videotapes of the performance were manually digitised using a Peak Motion Measurement System (Peak Performance Technologies, Denver, CO, USA), from four fields before the arm entry into the water to four fields after the completion of two consecutive stroke cycles. In each digitised field, 21 body landmarks were digitised to define a 14-segment model of the human body. The resulting sets of two-dimensional coordinate data were used as input to custom software that generated the corresponding three-dimensional coordinates, and expressed these with respect to the global reference system (Yanai et al., 1996). The three-dimensional coordinates were smoothed using a Butterworth filter with an estimated optimum cut-off frequency of 7.4 Hz (Yu, 1988).

Each body segment was modelled as a frustum of cone and the dimension was defined to match the segmental parameter data reported in the literature (density & relative mass – Clauser et al., 1969; and relative position of the centroid– estimated from the data presented by Clauser et al., 1969). The mass and the density of each body segment were used to determine the volume of the body segment (Figure 2). The radius of each end of the frustum was defined so that the centroid of the frustrum matches the cadaveric data of the centroid of the body segment.




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

= mass / density

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

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

**Figure 2 -** Body **Segment** Model

The volume ($V_i$) and the centroid ($CB_i$) of each frustrum under the water surface were then computed numerically, assuming that the water surface was horizontal. The z-coordinate of the water surface was measured when the water was still. The total volume of the body under the water surface was computed as the sum of the volumes of all frusta of cone under the water surface. The total volume was multiplied by the specific weight of the water and the buoyant force acting on the whole body was determined. The moment of the $V_i$ about the origin of the global reference system was summed for all body segments and divided by the total volume of whole body under the water surface, and the position vector of the centre of buoyancy of the whole body (CB) was determined. Finally, the buoyancy torque was determined as the cross product of the vector from the centre of mass of whole body to the CB and the vector that represents the buoyant force.

Computer simulation was used to analyse the effects of the individual variability in segmental parameters on the buoyancy torque. Two simulations were conducted for the analysis. The first was to determine the position of the CB relative to the CM in the sagittal plane, when the model was configured in a streamlined position and completely immersed in the water. For validity purpose, the relative position of the CB was compared with the corresponding value measured from 25 male swimmers in the study by McLean and Hinrichs (1998). The effect of variability in individual segmental parameters on the relative location of CB was also determined. The second simulation was to determine the effect of variability in individual segmental parameters on the magnitude, and the time-course of change in the buoyancy torque generated throughout the stroke cycles. For the set of kinematic variables obtained from the swimming trial, the values of density and relative position of centroid were changed in the range from -10 to 10 %, and their effects on the buoyancy torque were determined. The water surface level was also simulated to change in the range from -0.1 to 0.1 m, so that the possible effect of waves on the buoyancy torque could be examined.

**RESULTS AND DISCUSSION:** The buoyancy torque attained its peak value in the middle of the recovery phase, reaching approximately 13 Nm for both sides. The direction of the buoyancy torque changed from one direction to the other for each stroke cycle. Fourier analysis of the time-course of change in the buoyancy torque showed that the components that attained large amplitudes were concentrated on the frequencies in the range from the stroke frequency to the kick frequency. This indicates that the buoyancy torque was not constant and oscillated harmoniously with the stroking movements.

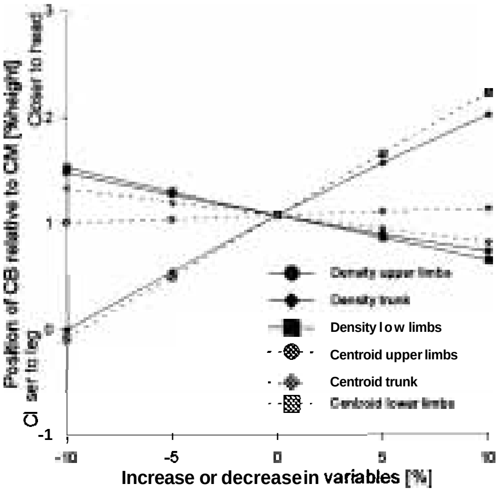



**Figure 3 - Position of CB relative to CG for a simulated streamlined swimmer**

The CB of the model in a streamlined position was found to be located at 1.08 % of the height closer to the vertex than the CM. This result was similar to the value (1 ± 0.1 % of height) reported by McLean and Hinrichs who measured the distance between the CB and CM of 25 male collegiate swimmers who were completely immersed in the water in the streamlined position. The computation of the CB was sensitive to the change in value of the density and centroid position of the trunk (the slopes of the regression line were 0.102 and 0.108, respectively). These results suggest that the accuracy in the computation of the CB in the longitudinal direction might be affected substantially by the amount of air inhaled by the subject. The inhalation of air, however, should not influence the accuracy in the computation of buoyancy torque, because it does not change the magnitude of the moment arm about the longitudinal-axis of the body.

The effects of the variability in the segmental parameters (centroid, density) and water surface height on the time-course of change in the buoyancy torque are presented in Figure 4. The changes in the centroid and density by ± 10% did not alter the pattern of change in the buoyancy torque, indicated by the correlation coefficient being 1.00 for any pair of combinations within the range. The root mean square (RMS) of the buoyancy torque over two stroke cycles was increased or decreased by 3 % due to the change in centroid position and by 9 % due to the change in density (Figure 5). It is not likely, however, that the RMS varies by 9 %, as the density of the competitive swimmer is unlikely to be greater or smaller by 10 % from the density of the model. The variability in the density is generally in the range of ± 3 % of the mean value for each body segment, according to the data presented by Chandler et al. (1975) and Dempster (1955). For male competitive swimmers, the percent body fat was reported to be 12.6% ± 3.8% (McLean and Hinrichs, 1998). On the basis of Siri equation (Siri, 1956), 12.6 ± 3.8 percent body fat is equivalent to the density of 1.07 ± 0.01 g/cc. The density of the whole body of the model used in the present study was 1.04 g/cc, which was 2.8 % smaller than the estimated density of the competitive swimmers. One reason for this difference might be that the Siri equation determines does not including the air in the lungs.

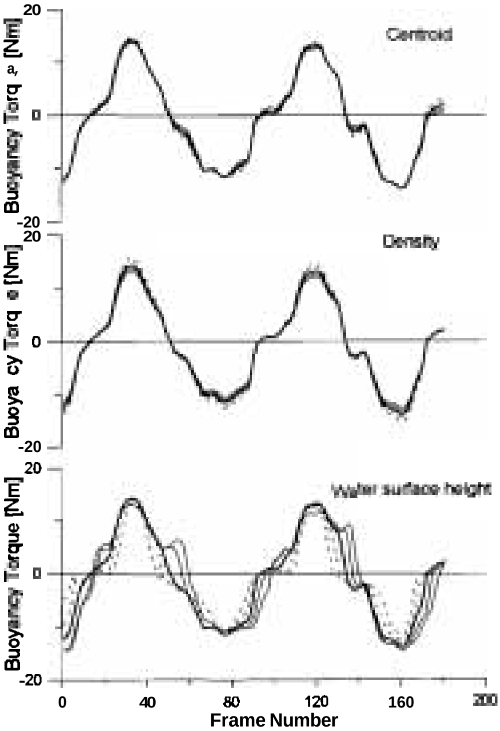



**Figure 4 - Buoyancy torque over two stroke cycles for different values for each segmental parameter (± 10%) and water surface height (± 0.1 m)**

The difference in the density between the model and male competitive swimmers should, therefore, be within ± 3 %, suggesting that the model segments well represent the body segments of male competitive swimmers. In computing the buoyancy torque, the error associated with the individual variability in body segment parameters of ± 3 % is estimated to be less than 3 %, according to Figure 5.

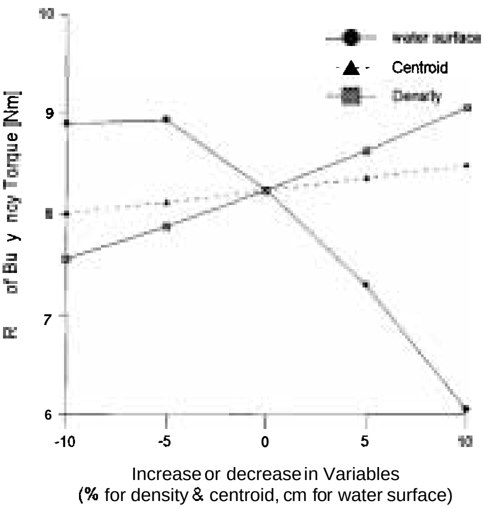



**Figure 5: The effect of variability in segmental parameters on Root Mean Square (RMS) of buoyancy torque for two stroke cvcles**

An increase or decrease in the height of the water surface (± 0.1 m) affected the buoyancy torque substantially (Figure 5). The RMS of the buoyancy torque was influenced in the range from -26 to 8 %. The maximum torque value, however, was not affected substantially (± 2 Nm). The pattern of change in the buoyancy torque was not altered for two stroke cycles, as indicated by the high correlation coefficient (≥ 0.92) for any combination of the time-course of change in the buoyancy torque. The water surface height might change due to the waves created by the movement of the swimmer. This might affect the computation of the buoyancy torque acting on those body segments that are partially submerged in the water. The wave might increase the height of the water surface in the front part of the body segment and decrease the height in the rear part. This wave effect might cause an error in computing the buoyancy torque about the transverse-axis to a certain degree, but it should not about the long-axis. The error associated with the assumption of horizontal water surface in computing the buoyancy torque is therefore expected to be limited.

**CONCLUSION:** A method was developed to determine the buoyancy torque to a known degree of accuracy. With this method, the effects of the buoyancy torque on body-roll can be described in detail, which will help sports scientists and coaches to understand the mechanics of body-roll in front-crawl swimming.

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