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Abstract

We investigated the rotational effect of buoyant force around the body's transverse axis, termed buoyant torque, during a 200m front crawl maximal swim. Eleven male swimmers of national or international level participated. One stroke cycle (SC) for each 50m was recorded with two above and four below water cameras. The following variables were analysed: swimming velocity; absolute and normalised buoyant force; minimum, average and maximum buoyant torque; SC and arm recovery times. The average value of buoyant torque was higher in the first 50m (14.2 ± 4.5Nm) than in the following 150m (9.3 ± 4.1Nm~10.9 ± 4.5Nm) and was directed to raise the legs and lower the head throughout the race. The change in its magnitude seemed to be linked to the shorter time spent proportionally in arm recovery (first 50m: 27.6% of SC time; next 150m: 23.3-24.4% of SC time). Most swimmers had periods of the SC where buoyant torque was directed to sink the legs, which accounted to 10% of SC time in the first 50m and about twice this duration in the next 150m. These periods were observed exclusively when the recovering arm had entered the water while the opposite arm was still underwater, but not all such periods showed leg-sinking buoyant torque.

Key words: Biomechanics, swimming, flotation, torque, three-dimensional videography.

Introduction

When a human body is immersed in water motionlessly, it is subject to two vertical forces: buoyant force and body weight. The stability of the body then depends on the relationship between the locations of these two forces. If the lines of action of the two forces are the same the body is in a stable or neutral position (Figure 1). If buoyant force acts more cranially than weight there is a tendency for the lower limbs (referred to as 'legs' from this point onwards) to sink, due to the torque generated around the centre of mass (CM). This torque is named 'buoyant torque' in this paper. If buoyant force acts more caudally than weight then the buoyant torque causes the head to sink and the legs to raise.

Insert Figure 1 near here

When a motionless human body is placed in water in a horizontal streamlined position, the buoyant force normally acts more cranially than the weight, generating the buoyant torque that lowers the legs and raises the head (McLean and Hinrichs, 1998; Payton and Reid, 2004; Yanai, 2001). The reverse is much less common, but it could be the case in some -or a combination- of the following situations: heavy muscular arms are extended above the head, a person has a little volume of air in their lungs, a person has a large amount of adipose tissue around the hips and thighs, and a person has a physical disability such as an amputated lower limb. The effect of buoyancy on body position and alignment is thought to influence the energy cost of swimming and, subsequently, swimming performance (e.g. Pendergast, Di Prampero, Craig Jr, Wilson and Rennie, 1977). It has been assumed that when the legs tend to sink a swimmer would experience increased drag and would have to increase the intensity of flutter-kicks to elevate the legs and maintain a more hydrodynamic position, therefore requiring more energy. However, when exploring the effect of buoyant torque on body position in dynamic conditions, for example when swimming, one needs to also consider the shifts of the CM and centre of buoyancy (CB) during a stroke cycle (SC), as the buoyant torque effect may change. For example, Yanai (2001) tested competitive swimmers at sub-maximal pace (1.6m/s) and

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reported that the CM fluctuated 2.3cm and the CB 10.5cm in front crawl swimming, with the CM shifting cranially and the CB caudally during the recovery phase. The former relates to the fast movement of recovering upper limb (referred to as 'arm' from this point onwards) cranially, while the latter is explained by the fact that the arm and part of the head are above the water and not subject to buoyancy. These movements generate buoyant torque that makes a leg raising rather than leg sinking effect in front crawl swimming.

Despite the above, practical experience suggests that the legs tend in fact to sink very often during swimming, for example when swimmers perform arm-only drills the legs would sink unless a buoyancy aid (e.g. a pull-buoy) is used. Thus, the question that arises is what is the cause of the leg-sinking tendency during swimming, if not the buoyant torque? Yanai and Wilson (2008) hypothesised that the hydrodynamic forces acting on the hands during the underwater phase of the upper limb motions, called arm stroke, generate a leg-sinking effect, which the swimmers then counterbalance with their flutter-kicking actions.

Nevertheless, as the effects of buoyancy have not been fully explored in swimming, one cannot be conclusive about its role on body rotation around the transverse axis and on floatation. For example, it has been reported that technique deteriorates during 200m maximum trials, with swimming speed decreasing significantly during the race (Figueiredo, Zamparo, Sousa, Vilas-Boas, & Fernandes , 2011; Psycharakis & Sanders, 2008). Some authors attribute this performance decrease to possible fatigue developed during a race, as swimmers have been reported to have reduced stroke efficiency, increased neuromuscular fatigue and higher lactate concentration towards the later stages of the race (Figueiredo et al., 2011; Figueiredo, Rouard, Vilas-Boas, & Fernandes 2013). Changes in swimming kinematics associated with possible development of fatigue and technique deterioration during a race may also affect the CM and CB interaction. Thus, to understand better the role of buoyancy in swimming, research on the effects of buoyancy during the course of a maximal trial is warranted.

As the CM and CB interaction is crucial in understanding the effects of buoyancy on swimming performance, consideration should be given to factors that might affect this interaction during swimming. For example, the time spent on arms' recovery during a SC has not been reported in previous buoyancy studies. Recovery time would be useful in providing an indication of the percentage of the SC that the arms are submerged or above the water. Moreover, only minimum, maximum and average values for the overall leg-sinking or leg-raising effect of buoyant torque have been reported previously (Yanai, 2001). It would be interesting to know at which parts of the SC buoyant torque is directed to raise the legs or sink the legs, as well as how much time of the SC is spent at each of those two conditions. Furthermore, early studies in this area calculated buoyant torque for a mixture of breathing and non-breathing SCs, without controlling for or calculating the breathing effects (McLean and Hinrichs, 1998; Yanai, 2001). However, given that turning the head to take a breath is expected to alter the determined values of buoyant force and torque and swimming kinematics (Psycharakis and McCabe, 2011), such calculations may have masked the actual effects of buoyancy on performance. Thus, it is important that studies control for the effects of breathing on buoyancy calculations.

Finally, with the advancement of technology modern methods can allow more accurate calculation of variables with substantially lower errors in measurements, which can increase our confidence in findings and enhance their generalisability and applicability. For example, in an early study two panning periscopes were used to conduct the three-dimensional (3D) analysis of buoyancy in swimming (Yanai, 2001). It has been recommended that at least six cameras are used in order to increase the processing accuracy and reliability. Such a set-up would also improve marker visibility and reconstruction reliability, as it would ensure that the vast majority of markers are always visible by at least two cameras to minimise the incidence of 'guessed' points and missing data (Psycharakis and Sanders, 2008).

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The purpose of the present study was to quantify the buoyant torque during a 200m maximal front crawl swim and explore any changes that occur during the race. To fill in the gaps in previous research and improve our understanding on the mechanisms behind any effects, other aims of this study were to focus on non-breathing stroke cycles, to investigate whether recovery times change during the race and to use methods and equipment that increase the accuracy and reliability of the measures.

Materials and Methods

Participants

Eleven male swimmers (16.9±1.2 years, 180.8±5.7cm, 71.4±5.6kg, personal best in 200m front crawl: 121.5±5.7s) volunteered to participate in this study. All swimmers were competing at national or international level, were free from injury and illness and avoided stressful training in the days prior to testing. Ethical approval was granted by the institutional ethics committee and all swimmers signed informed consent forms before the study commenced.

Experimental design and data collection

On the testing day each swimmer performed a personalised warm up in a 25m indoors swimming pool. Following a 20-min passive rest, to simulate a race scenario, each swimmer performed a 200m maximum front crawl test and was asked to replicate their competition pacing and strategy. The swimmers started with a push start from the water to avoid the dive influencing the kinematics of the first SC used in the analysis. To eliminate any breathing effects on CB and CM positions, swimmers were instructed to take a breath just before the 6.5m-long pre-calibrated space and then hold it while swimming through this space. The 200m front crawl was one of the specialist events of all participants. To ensure that tests were representative of competition performance, they were subsequently analysed only if performance time was within 105% of a swimmer's personal best time, to also allow for the

slightly slower times due to the push start used in the test. All swimmers satisfied these criteria when first tested, with test time being on average 3% slower than personal best time.

Six stationary, synchronised and genlocked JVC-KY32CCD cameras (four under and two above the water, frequency 50Hz) recorded the trials. The underwater cameras recorded the same space in the middle of the pool, which had a length of approximately 6.5m, allowing collection of data of a full SC. The camera and calibration set-up is described in detail by Psycharakis, Sanders and Mill (2005), who indicated that this set-up has negligible image distortion and refraction, high accuracy and reliability, and produces small and acceptable calculation errors that are in general similar to or better than other studies that used similar calibration volumes (e.g. De Jesus *et al*., 2015). In addition, a complete SC of one swimmer was digitised 5 times for all six cameras. The standard deviation (SD) and coefficient of variation (CV) of the average SC velocity across all digitisations was calculated as an indication of reliability. The calculations indicated good reliability, with the SD and CV values being 0.002 m/s and 0.09% respectively.

Data analysis

Four SCs (one for each 50m) were analysed for each swimmer. Although analysis of more SCs per 50m would have been useful, the biomechanical facility and the set-up for 3D data collection in the current study did not allow for capturing more than one SC per 50m. All swimmers were right-handed and the SCs were defined as the period between two consecutive hand entries of the left hand. The Ariel Performance Analysis System (APAS, Ariel Dynamics Inc., California) was used to digitize 19 body landmarks for each field (vertex; shoulders, elbows, wrists, hips, knees, ankles, metatarsophalangeal joints; end of middle fingers and big toes) so that the subject's body was modelled as a linkage of 16 rigid segments consisting of head, torso (upper, middle & lower portions), upper arms, forearms, hands, thighs, lower legs and feet. The resulting sets of two-dimensional coordinates were used to determine the corresponding 3D coordinates and were expressed with respect to a global reference system

embedded to the pool deck at the water surface. The global reference system was defined with the x-axis pointing in the swimming direction, the y-axis pointing vertically upwards and the z-axis perpendicular to the swimming direction pointing from the left to right of the swimmer. The 3D coordinates were smoothed using a Fourier transform and inverse transform by retaining harmonics up to 6Hz in the inverse transform. The 3D reconstruction and the calculation of the CM velocity were performed as described by Psycharakis and Sanders (2008). Recovery time for each arm was calculated as the time between hand exit after the underwater phase and same hand entry, divided by the overall time of the SC.

The method identical to the one described by Yanai (2001) was used to determine the buoyant force and buoyant torque. The buoyant force was determined as the product of the specific weight of the water ($9790N/m^3$) and the volume of all body segments located under the water surface. The volume and centroid of the body under the water surface was computed numerically for every field for the given positions and orientations of the 16 body segments in the field and the dimensions of the body segments estimated on the basis of body segment parameters reported in the literature (density and centroid – Drillis and Contini, 1966; mass – Clauser, McConville, Young and Weight, 1969; CM – Hinrichs, 1990). The lung volume of the subjects was approximated to be 4.2lt as the sum of the residual volume (1.96lt Armour and Donnelly, 1993) and the tidal volume measured during front crawl swimming (2.0~2.5lt reported by Ogita and Tabata, 1992; 2.3lt by Town and Vanness, 1990). The water surface level was approximated as two consecutive sine waves to model the "three-waves" pattern described by Firby (1975). The wave length was equal to half the stature of the subject and the amplitude was estimated as a function of swimming speed (Yanai, 2001). The buoyant force was divided by each participant's body weight to provide a normalised value for comparison purposes. The buoyant torque was determined as the cross product of the vector directed from the CM to the centroid of the entire volume of all body segments under the water surface (named as the centre of buoyancy: CB) and the vector representing the buoyant force.

The component of the buoyant torque parallel to the z-axis, which influences the horizontal alignment of the body, was used for analysis.

<u>Statistical analysis</u>

Descriptive statistics were reported as the mean values ± standard deviation (SD) and the 95% confidence interval (95%CI) for the whole group. Normality of distribution was assessed with the Shapiro-Wilk test. As data were parametric, a repeated measures analysis of variance (ANOVA) was performed between the four SCs to identify changes during the 200m. When sphericity was violated the Greenhouse-Geisser adjustment was applied. Post-hoc comparisons were performed to compare all pairs of SCs and the Bonferroni adjustment was applied to eliminate the possibility of type I errors. To provide an indication of the magnitude of differences, the effect sizes (ES) were calculated based on Cohen's suggestions, with each pooled SD being calculated as described by Field (2009). In line with Cohen's recommendations, effect sizes of a magnitude of 0.2, 0.5 and 0.8 were considered small, moderate and large respectively. For all statistical analyses significance was accepted at $p \leq 0.05$.

Results

Table 1 shows the values for swimming velocity, buoyant forces and torques throughout the 200m swim, the maximum and minimum distance between the CB and CM, and the statistical analysis for all variables. Velocity decreased as the race progressed, as often expected, with an overall drop of 13.2% from SC1 to SC4 and with the ES being very large ($0.92 \leq d \leq 1.13$). The buoyant force was lower in the first SC than all subsequent SCs. Although the ES for buoyant force were small ($0.20 \leq d \leq 0.27$), the ES for the normalised buoyant force were large ($0.98 \leq d \leq 1.42$). The average buoyant torque of each SC was directed to raise the legs throughout the 200m maximum swim, with large ES ($0.74 \leq d \leq 1.15$) and with no swimmers experiencing the average buoyant torque in the opposite direction for any SCs during the test.

The leg-raising effect of buoyant torque was significantly higher in the first SC, compared to all subsequent SCs.

Insert Table 1 near here

Table 2 shows the values of SC time, recovery phase time and the time spent with buoyant torque acting in the leg-raising direction. SC time was significantly shorter in SC1 compared to the other SCs and the ES were large ($p \leq 0.001$, $0.79 \leq d \leq 0.87$). Although the actual time spent in recovery did not change during the 200m, the percentage of the SC time spent recovering the arms decreased significantly during the race, suggesting that swimmers spent longer periods of the SC in a more submerged position as the race progressed. The left arm recovery, when expressed as a percentage of the SC duration, was significantly longer in SC1 compared to the other SCs, with moderate to large ES ($0.002 \leq p \leq 0.049$, $0.73 \leq d \leq 1.13$). Swimmers spent less time in the SC with buoyant torque acting in the leg-raising direction as the race progressed, but none of the pairwise comparisons reached significance despite the moderate to large ES ($0.74 \leq d \leq 0.89$). Three of the 11 swimmers had between one and three SCs with buoyant torque acting in the leg-raising direction throughout, with the remaining SCs showing both leg-raising and leg-sinking effects. The buoyant torque in the leg sinking direction (i.e. negative buoyant torque) was observed exclusively during periods of the SC that the arm was entering the water while the opposite arm was still underwater. However, not every such overlap between the arms resulted to buoyant torque in the leg-sinking direction.

Insert Table 2 near here

Discussion

The purpose of this study was to quantify the rotational effect of the buoyant force during a 200m maximal swimming trial and explore any changes that occur during the race. This is the first study to explore the changes in the effects of buoyant force and torque during a maximal

trial and also the first study to calculate buoyant force and torque in 3D using multi-camera systems both above and below the water surface. Together with the elimination of errors from non-consideration of potential effects of breathing action to buoyancy, this study provides a rigorous analysis that allows generalisability of the findings. The results indicated that the buoyant force decreased significantly after the first 50m. Buoyant torque had a net leg-raising effect throughout the 200m, which was significantly larger in the first 50m compared to the next 150m. Stroke cycle time increased after the first SC, with swimmers decreasing the time spent proportionally on arms' recovery and increasing the time the arms spent in the underwater phases of the arm stroke.

A potential source of error for the present study may be the method used to determine buoyant force and torque. The accuracy of this method has been reported by Yanai (2001). An error in estimating lung volume by 1.0 l was reported to cause the mean value of the buoyant torque over a SC to change 1.0Nm (Figure 6 of Yanai, 2001) whereas the standard deviation of the lung volume (residual volume + tidal volume) was estimated to be 1.0 l (Armour and Donnelly, 1993; Ogita and Tabata, 1992; Town and Vanness, 1990). If the change in buoyant torque observed between the SC1 and the other SCs (about 4Nm) were totally due to the error in estimating the lung volume, the amount of error should have been 4.0 l, four times as large as the standard deviation of the lung volume. It seems unrealistic to assume such a large error occurred consistently among all subjects, suggesting that the present findings should not be explained by the error in estimating the lung volume. An overestimation of the wave amplitude by 50% causes an underestimation in the mean value of the buoyant torque over a SC by 3.5Nm (Figure 7 of Yanai, 2001). If the reductions in buoyant torque observed in SC2, SC3 and SC4 (about 4Nm) were thoroughly attributable to an overestimation of the wave height in these SCs, the true wave heights must have been 18±1 mm (instead of the estimated values of 36±2mm) in comparison to 40±2 mm in SC1. Such a large drop in wave height after the first 50m should be recognisable during the data collection and also on the video images, but no evidence was found even after repeated careful observations of video recordings. Although

the errors were involved in the computation of buoyant torque, it does not alter the main findings of the present study that the buoyant torque had a net leg-raising effect throughout the 200m and the leg-raising effect decreased after the first 50m. Therefore, we are confident to suggest that the change in buoyant torque across the SCs was primarily due to the change in kinematics (position and orientation of each body segment), rather than the possible errors in estimating lung volume and wave amplitude.

Effect of buoyancy on front crawl swimming

The results of this study indicate that buoyant torque has a clear overall leg-raising effect throughout a 200m maximal front crawl swim, despite any technique changes or possible race-related fatigue. This is contrary to early theories that buoyant torque causes the legs to sink during front crawl swimming and confirms the observations of Yanai (2001) during a sub-maximum 23m swimming test (mean swimming velocity 1.6m/s). Thus, it can be argued that the net effect of buoyant torque during a non-breathing SC helps to enhance front crawl performance, as the leg-raising torque facilitates the maintenance of a streamlined position of the legs, limiting the need for additional effort of executing flutter-kicks used for this purpose and, therefore, the energy required. One, however, could also argue that a leg-raising buoyant torque tends to create a head-sinking effect, which could disturb the hydrodynamic position and might require additional energy from the arms to maintain this position. The arms are however the primary source of propulsion in front crawl swimming and they are expected to produce head raising torques at the pull phase of the underwater arm stroke. Thus, it would not be unreasonable to assume that any head-sinking effects of buoyant torque can be easily controlled by the torques produced by the arms, requiring less energy than a swimmer would need to overcome a leg-sinking effect.

The magnitude of leg-raising buoyant torque in the current study (from 9.3Nm to 14.2Nm) was lower than that reported by Yanai (2001) when testing at 1.6m/s (22.4Nm). A possible explanation for this difference could be the use of non-breathing SCs in the current study, as

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opposed to both breathing and non-breathing SCs used in the 2001 study. During non-breathing SCs it is likely that a greater portion of the head and the shoulder would be submerged than during breathing SCs, which means that a larger volume of the body located cranial to the CM is subjected to buoyant force during the arms' recovery. In line with this, the data presented in Yanai's study (Figure 5 of Yanai, 2001) showed clearly that the CB shifts caudally to a considerably greater extent in the recovery phase with breathing than the following recovery phase in the same side with no-breathing, having caused the buoyant torque during the recovery phase with breathing to be substantially greater. A simulation study (Yanai and Wilson, 2008) indicated that the CB position would be displaced cranially by 1.5% of the stature if half the head and one side of shoulder were submerged in water (Figure 2). This amount of CB displacement would account for a reduction in the buoyant torque by about 17Nm during the recovery phase for our subjects. Another possible explanation for the differences could be that swimmers in the 2001 study were 1% taller and 8% heavier than swimmers in the present study, which could directly affect the magnitude of the buoyant torque. Indeed, the normalised buoyant force ranged from 88%BW-91%BW, which is very similar to the current study (89.8%BW-91.7%BW).

Insert Figure 2 near here

The periods within a SC where buoyant torque was directed to raise the legs were observed exclusively when the recovering arm of the swimmers had entered the water while the opposite arm was still underwater. This is logical as during that phase of the SC the CB would be expected to shift cranially, as both arms are submerged, while the change in the CM would be minimal. The buoyant torque switched to leg-raising when the opposite arm started exiting the water, which was also reasonable as the start of the arm recovery would be expected to cause a substantial shift of the CB caudally. With the swimmers spending proportionally more time underwater as the race progressed, the time spent with a leg-sinking buoyant torque seemed to increase from about 10% of the SC time in the first 50m to approximately twice as long in the

following 150m. The reasons for the change in the time spent in the underwater phases may lie on technique deterioration during the 200m. Figueiredo et al. (2013) reported that the arms reached sub-maximal fatigue during a 200m maximal test. Thus, it is possible that swimmers moved their arms slower underwater because of the muscular fatigue, causing longer durations for this phase.

Change in the magnitude of the effect of buoyancy

The magnitude of the leg-raising buoyant torque was significantly larger in the first SC compared to the rest of the race. This change could be linked to two factors, swimming velocity and duration of recovery phase. The first link may be described as follows: For each swimmer, the swimming velocity was faster in SC1 than the other SCs by about 10%. The higher swimming velocity in SC1 should be caused primarily by a greater amount of hydrodynamic forces acting on the hands in SC1. The greater amount of hydrodynamic forces acting on the hands should generate a greater leg-sinking effect as they act eccentric to the CM during the underwater phase of the arm stroke and, thus, the flutter kicks need to be executed with an increased intensity to counterbalance the increased leg-sinking effect of the hydrodynamic forces. The near vertically directed hydrodynamic forces generated by the flutter kicks and the vertical component of the hydrodynamic forces acting on the hands should be greater in SC1, causing the swimmer's body to ascent and a greater portion of the head, recovery arm and shoulder to emerge above the water surface. The total volume of the body under the water surface decreases and the CB shifts caudally (Figure 2), as a consequence. With this mechanism, a given swimmer's SC with a faster velocity could result in a reduced buoyant force and increased buoyant torque. In fact, further examination of the data showed that the swimmers raised their arms and head higher during the recovery phase in the first 50m and lesser as the race progressed, supporting the theoretical link between the swimming velocity and the magnitude of buoyant torque. The second link may be described as follows: The swimmers spent proportionally less time recovering their arms after the first SC, which suggests that they were more submerged in the water and had a shorter average distance of CB

and CM over the SC. Indeed, swimmers were shown to spend almost twice as long at positions with leg-sinking buoyancy effects after the first 50m, as after each hand entry the opposite arm seemed to remain submerged in the water for longer.

Given the decrease observed within each swimmer in the magnitude of the leg-raising effect of buoyant torque over the course of 200m race, it would be interesting to explore the possibility of any particular patterns associated across the swimmers of various swimming levels, i.e. if faster swimmers had higher values or smaller changes in buoyant force. A correlation was therefore performed between the swimming velocity and: the buoyant force, the buoyant torque, the change in buoyant force and torque over the 200m and the time of the SC over which buoyant torque had a leg-raising effect. There were no significant correlations, showing no distinct patterns for faster swimmers in terms of the magnitude of leg-raising effect or its change during the 200m. This suggests that the between-subjects variance in the buoyant force and the buoyant torque is not directly related to the swimming velocity, revealing a difference between the within-subject effect and the between-subjects effect in the relation between the swimming velocity and the buoyancy. These findings together suggest that the between-subjects variance in swimming velocity is influenced more directly by the variance among subjects in swimming techniques (changing pattern of the position and orientation of each body segment during SC) and/or the body dimensions, than by the variance in buoyant force and buoyant torque. It is also possible that the group of swimmers tested in the current study was too homogenous to reveal significant between-subjects effect, so this hypothesis should be confirmed in future studies by expanding to swimmers of a larger range of velocities and skills.

Although the pattern of change in the magnitude of the leg-raising effects of buoyant torque in the current study suggests that the leg raising effect would be even higher during faster events such as 50m and 100m sprints, further research on other swim distances would still be very useful in providing an even better understanding of the role of buoyancy in the full range

of swimming speeds. The rate of reduction of the leg raising effect with the drop in speed and the fact that longer distance events are performed with frequent breathing also suggests that it is perhaps unlikely that in longer distance events buoyant torque would have a leg sinking effect. Nevertheless, swimmers in longer distance events may spend more time of the SC with both arms submerged, so further research in other distances and in breathing cycles would be useful in facilitating generalisation of the findings of the current study to all distances. There is also some evidence in the literature to suggest that leg-sinking effect of buoyant torque acting on a horizontal motionless swimmer may be correlated to energy cost of swimming, in particular, for slow speeds (up to 1.2m/s), and may also be affected by the gender and skill level of a swimmer (Pendergast *et al*., 1977; Zamparo, Capelli, Cautero and Di Nino, 2000). Although the buoyant torque acting on a swimmer in a horizontal motionless position has a different effect to that during swimming (leg sinking and leg raising, respectively; Yanai, 2001), its link to the energy cost of swimming should also be further explored in future studies. Finally, as mentioned in the introduction, experience suggests that the legs tend in fact to sink during swimming if flutter kicks are not executed. As buoyant torque is not the cause of this phenomenon, other possible determinants should now be explored in more depth, such as the moment of the hydrodynamic forces actively generated by the arm actions during the underwater phase of the arm stroke and the moment of the passive drag and lift acting on the head and the upper torso of the swimmer.

Conclusions

During a 200m maximal swim trial buoyant torque has a net leg-raising effect throughout the race. This effect is higher in the first 50m than in the following 150m. The change in the magnitude of the effect seems to be linked to the shorter time the swimmers spend proportionally in recovering their arms. Most swimmers had periods of the SC where buoyant torque had a leg-sinking effect, which accounted to 10% of the SC time in the first 50m and about twice this duration in the rest of the race. These periods were exclusively observed when

one arm was entering the water while the opposite arm was still in the water, but not all such periods resulted into leg-sinking effect for buoyant torque.

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Figure Legends

Figure 1: The position of the centre of buoyancy relative to the centre of mass of the body determines the stability of the floating body (Yanai and Wilson, 2008- reprinted by permission).

Note: The centre of buoyancy is located directly above the centre of mass on the first sketch whereas the centres of buoyancy and mass are located at the same point in the second sketch.

Figure 2: Schematic presentation of the effect of half the head and one shoulder submerged in or emerge from the water on the position of centre of buoyancy.
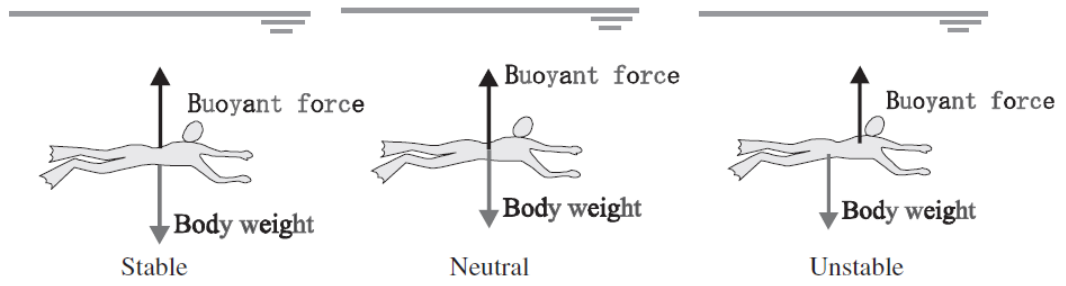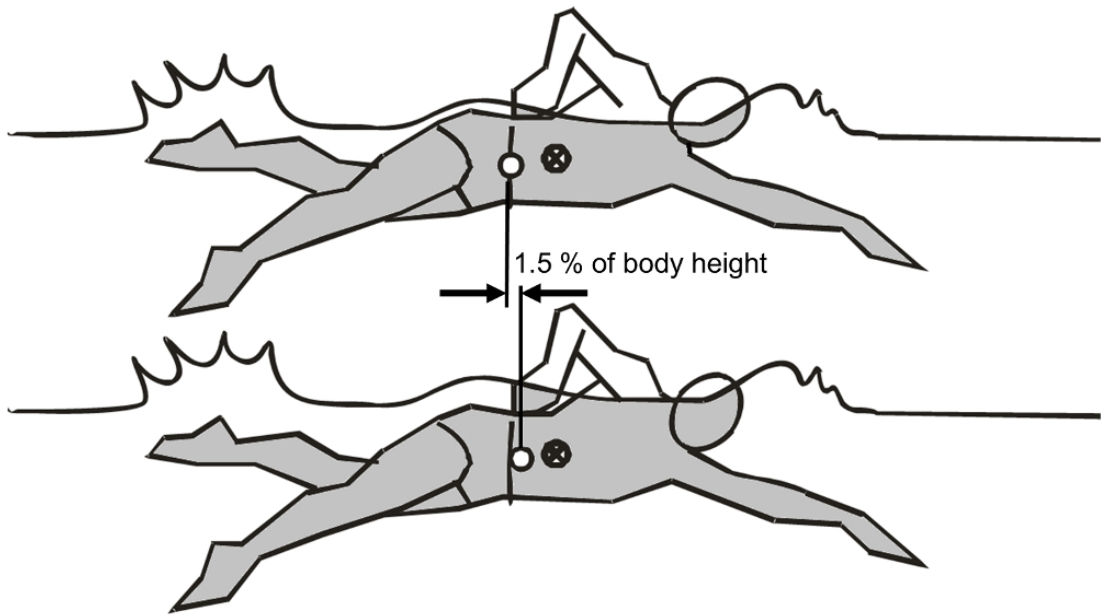
Figure 1

Figure 2

1.5 % of body height

Table 1: Mean ± SD values for the kinematic and kinetic variables during the 200m maximum swim. 95%CI are shown in brackets.

Variable	SC1	SC2	SC3	SC4	Mean	ANOVA
Swimming Velocity (m/s)	1.66±0.06 (1.62-1.70)	1.50±0.08 [a] (1.46-1.55)	1.46±0.08 [a,b] (1.41-1.51)	1.44±0.06 [a,bb] (1.40-1.47)	1.51±0.06 (1.48-1.55)	$F_{3,30}=92.2$ $p<0.001$
Buoyant Force (N)	631.4±52.1 (601-662)	641.3±48.3 [a] (613-670)	643.9±47.8 [a] (616-672)	644.9±48.5 [a] (616-674)	640.4±49.0 (611-669)	$F_{3,30}=15.5$ $p<0.001$
Normalised Buoyant Force (%BW)	89.8±1.5 (88.9-90.7)	91.2±1.4 [a] (90.4-92.1)	91.6±1.3 [aa] (90.8-92.4)	91.7±1.2 [a] (91.0-92.5)	91.1±1.2 (90.4-91.8)	$F_{3,30}=14.9$ $p=0.002$
Average Buoyant Torque (Nm)	14.2±4.5 (11.5-16.9)	10.9±4.5 [aa] (8.2-13.5)	9.7±4.1 [aa] (7.2-12.1)	9.3±4.1 [a] (6.9-11.7)	11.0±3.9 (8.7-13.3)	$F_{3,30}=12.8$ $p<0.001$
Minimum Buoyant Torque (Nm)	-5.2±6.5 (-9.0-(-1.3))	-5.6±5.4 (-8.8-(-2.4))	-7.1±5.7 (-10.5-(-3.8))	-4.6±4.3 (-7.1-(-2.0))	-5.6±4.6 (-8.4-(-2.9))	$F_{1.7,16.6}=1.1$ $p=0.356$
Maximum Buoyant Torque (Nm)	32.7±9.9 (26.9-38.6)	29.5±8.9 (24.2-34.8)	26.5±6.9 (22.4-30.5)	25.7±7.9 (21.0-30.4)	28.6±7.3 (24.3-32.9)	$F_{3,30}=4.6$ $p=0.009$
Minimum Distance between CB-CM (mm)	-0.055±0.020 (-0.067 – (-0.044))	-0.049±0.014 (-0.057 – (-0.040))	-0.044±0.012 (-0.051 – (-0.037))	-0.043±0.014 (-0.051 – (-0.035))	-0.048±0.013 (-0.056 – (-0.040))	$F_{3,30}=4.9$ $p=0.007$
Maximum Distance between CB-CM (mm)	0.008±0.009 (0.002-0.013)	0.010±0.006 (0.006-0.013)	0.011±0.008 (0.006-0.016)	0.012±0.006 (0.008-0.015)	0.010±0.007 (0.006-0.014)	$F_{3,30}=1.9$ $p=0.149$

Notes: For buoyant torque, positive values indicate a leg-raising and negative values a leg-sinking effect. CB stands for Centre of Buoyancy and CM for Centre of Mass. For distance between CB and CM, positive values indicate that CB is located cranial to CM (causing leg-sinking torque).

[a]: significantly different to SC1at $p<.01$. [aa]: significantly different to SC1at $p<.05$

[b]: significantly different to SC2at $p<.01$. [bb]: significantly different to SC2at $p<.05$

Table 2: Mean ± SD values for the temporal variables during the 200m maximum swim. 95%CI are shown in brackets.

Variable	SC1	SC2	SC3	SC4	Mean	ANOVA
Stroke Cycle Time	1.27±0.15	1.42±0.20 [a]	1.42±0.20 [a]	1.40±0.17 [a]	1.38±0.18	$F_{3,30}=21.9$
(s)	(1.18-1.36)	(1.31-1.54)	(1.30-1.54)	(1.30-1.50)	(1.27-1.48)	$p<0.001$
Right Arm Recovery	0.35±0.10	0.34±0.08	0.34±0.04	0.32±0.04	0.34±0.06	$F_{3,30}=5.1$
(s)	(0.29-0.41)	(0.30-0.39)	(0.31-0.36)	(0.30-0.34)	(0.30-0.37)	$p=0.031$
Right Arm Recovery	27.5±5.1	23.9±2.7	24.0±3.1	22.9±2.7	24.6±2.4	$F_{3,30}=1.3$
(%SC)	(24.5-30.5)	(22.3-25.5)	(22.1-25.8)	(21.4-24.5)	(23.1-26.0)	$p=0.304$
Left Arm Recovery	0.35±0.07	0.35±0.07 [aa]	0.34±0.07 [aa]	0.33±0.06 [a]	0.34±0.06	$F_{3,30}=9.5$
(s)	(0.31-0.39)	(0.31-0.39)	(0.30-0.38)	(0.30-0.36)	(0.31-0.38)	$p<0.001$
Left Arm Recovery	27.7±4.1	24.7±4.0	24.1±3.3	23.6±3.0	25.0±3.2	$F_{3,30}=1.2$
(%SC)	(25.3-30.1)	(22.4-27.1)	(22.6-26.1)	(21.8-25.4)	(23.1-26.9)	$p=0.309$
Time with Buoyancy having a	90.2±8.0	80.6±12.9	81.9±12.0	80.9±15.9	83.4±10.1	$F_{3,30}=3.1$
leg-raising effect (%SC)	(85.5-94.9)	(73.0-88.2)	(47.8-89.0)	(71.5-90.3)	(77.5-89.4)	$p=0.042$

[a]: significantly different to SC1 at $p<.01$. [aa]: significantly different to SC1 at $p<.05$