Determination of the Drag Coefficient During the First and Second Gliding Positions of the Breaststroke Underwater Stroke


The purpose of the current study was to assess and to compare the hydrodynamics of the first and second gliding positions of the breaststroke underwater stroke used after starts and turns, considering drag force ($D$), drag coefficient ($C_D$) and cross-sectional area ($S$). Twelve national-level swimmers were tested (6 males and 6 females, respectively 18.2 ± 4.0 and 17.3 ± 3.0 years old). Hydrodynamic parameters were assessed through inverse dynamics from the velocity to time curve characteristic of the underwater armstroke of the breaststroke technique. The results allow us to conclude that, for the same gliding velocities (1.37 ± 0.124 m/s), $D$ and the swimmers’ $S$ and $C_D$ values obtained for the first gliding position are significantly lower than the corresponding values obtained for the second gliding position of the breaststroke underwater stroke (31.67 ± 6.44 N vs. 46.25 ± 7.22 N; 740.42 ± 101.89 cm² vs. 784.25 ± 99.62 cm² and 0.458 ± 0.076 vs. 0.664 ± 0.234, respectively). These differences observed for the total sample were not evident for each one of the gender’s subgroups.

Keywords: swimming, passive drag, drag coefficient, hydrodynamic position

In swimming specialized literature it is possible to find a number of studies assessing the hydrodynamic passive drag in prone and dorsal positions with the arms together and stretched tightly overhead (shoulders flexed) during the glide (Clarys, 1979; Kolmogorov et al., 1997; Lyttle et al., 2000; Toussaint et al., 2004). However, there are other gliding phases during swimming actions, in which the swimmer assumes a prone position but places the arms extended at the sides of the trunk — that is the case of the second gliding position assumed during the breaststroke underwater armstroke. This second gliding position is only used during the starts and turns in breaststroke events. Probably because of this, the literature dealing with drag assessment in this particular position is scarce, particularly using experimental approaches. Marinho et al. (2009) studied this problem using Computer Flow Dynamics (CFD), a numerical modeling approach to hydrodynamic questions. The results of their work hint that the first gliding position of the breaststroke underwater armstroke is more hydrodynamic than the second one. Nevertheless, these are results extracted from modeling, therefore needing experimental ratification.

Starts and turns appear to be a significant part of the total swimming event time (Vilas-Boas & Fernandes, 2003). It has long (Thayer & Hay, 1984) been well known that starts may be responsible for less than 0.5% (1000-yard freestyle) to about 11% (50-yard freestyle) of the total competition time, taking slightly more than 3 s (9 m starting time) for the 200 m breaststroke. The same is also true for the swimming turns; they can amount to one-third of the total event time for distances of 200 yard or longer (Thayer & Hay, 1984), representing, for the 200 yard breaststroke, about 39% of the total racing time (11 m turning distance). Both during starts and turns, gliding phases occur, especially in breaststroke events. Chatard et al. (1990a) stated that the gliding phase after the start and turns corresponds to 10–25% of the total swim time (depending on events and a short or a long course pool),
and D’Acquisto et al. (1988) showed that, during the breaststroke events, the gliding phase represents 44% of the total swimming time. These last authors demonstrated that this phase is the one which distinguishes superior from good breaststroke swimmers, superior swimmers spending a greater amount of time gliding.

Considering the above arguments, it was considered pertinent to experimentally study both common gliding positions in swimming (prone position with the arms in a streamlined upper position and with the arms stretched along the trunk), with special reference to the drag force experienced by the swimmer. As a consequence, the purpose of the current study was to assess and compare: the hydrodynamic passive drag force ($D$); the hydrodynamic drag coefficient ($C_D$); and the swimmers’ cross-sectional area ($S$) during the first and second gliding positions of the breaststroke underwater stroke. We hypothesized that $D$ and $C_D$ will be higher in the second gliding position, mainly due to an increase in $S$ and a decrease in full body length, presumably resulting in a decreased in body slenderness.

**Methods**

Twelve national-level swimmers (6 males and 6 females) volunteered and gave written informed consent to participate in this study that was approved by the host institution ethical committee. Testing sessions were conducted in a 25 m pool, 2 m deep, with water temperature at 27.5 °C. The mean sample characteristics were, for male and female subjects, respectively: 18.2 ± 4.0 and 17.3 ± 3.0 years old, 178.2 ± 9.0 and 165.8 ± 3.9 cm of height, 64.4 ± 11.4 and 57.8 ± 4.9 kg of body mass, and 68.77 ± 1.59 s and 77.39 ± 2.86 s of mean performance time for 100 m breaststroke.

Body cross-sectional area ($S$) was determined through planimetry, using scaled photographs of the subjects (as proposed by Clarys, 1979). As shown in Figure 1, for this procedure, swimmers were photographed from above (in the transverse plane), at a height of 3.00 m measured from the ground reference plane, in two different positions: (i) standing up, shoulders flexed, with the arms together and stretched tightly overhead, and with one hand placed over the other, and (ii) as in the previous position, but with the arms stretched along the trunk. The metric calibration of the photos was obtained through a ruler placed at shoulder level. A Matlab (MathWorks, USA) routine was used to define the area of the swimmer’s $S$ in the image by decomposing it in a triangle system, and determining the total area through the summation of the triangles’ areas. The final result of this process was the mean value of 3 independent digitizing trials.

The passive drag was assessed through inverse dynamics (similar to the procedure proposed by Klauck & Daniel, 1976) based upon the velocity to time ($v(t)$) curve of each glide, monitored through a swim-meter (Swimsensor, Porto University, Portugal) developed by Lima et al. (2006). This is a cable swim-meter specially developed to avoid inertial effects over the cable, as well as effects of cable accumulation over the real perimeter of the reel, which rotational velocity is monitored through an incremental sensor (500 Hz). The accuracy of this swim-meter was previously tested for swimming speed fluctuation patterns over 28 trials of 7 swimmers, presenting mean correlation coefficient values of 0.96 ± 0.028 and 0.88 ± 0.053, respectively, for swim-meter hip kinematics vs. image-based hip kinematics, and swim-meter hip kinematics vs. center of mass (CM) kinematics (Lima, 2006).

Each swimmer performed 3 repetitions of the breaststroke underwater stroke, at maximal intensity, with over 2 min of recovery in between. During the rest interval between each repetition, the swimmer received proper feedback to improve his/her performance. The

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**Figure 1** — Body surface area determined through planimetry in the first (A panel) and second (B panel) gliding positions of the breaststroke underwater stroke. The feet projection was not considered due to the assumed difference relatively to the plantar flexed position in underwater conditions.
protocol was videotaped by one underwater camera (JVC GR-SX1 SVHS) fixed in the lateral wall of the pool, 15 m apart from the starting wall. The video images and the $v(t)$ curves were superimposed in real time using a mixing table (Panasonic WJ-AVE55) and a VCR (Panasonic AG 7350 SVHS).

For data processing the $v(t)$ curve representative of the best trial of each swimmer (Figure 2) was chosen—selected by an experienced coach—filtered with a 3 Hz cut-off low-pass 4th order Butterworth filter. For most of the cases the best trial was the 3rd repetition, showing a positive influence of the feedback given after each repetition.

The analysis of the output curves, and of their respective data were conducted during the first and second glides of the breaststroke underwater stroke, using as reference a glide divided into 4 phases from the push-off from the wall (Counsilman, 1986; Maglischo, 2003): (i) first gliding, (ii) arms action, (iii) second gliding and (iv) arms and legs recovery followed by the legs’ action toward the surface. In the $v(t)$ curve, a range of velocities common to both gliding phases were selected (Figure 3).

The range of velocities was chosen, case by case, based on the following criteria: (i) the larger the better; (ii) characterized by a continuous reduction in gliding velocity; (iii) not including actions other than gliding;
and (iv) avoiding excessive fluctuations in the original unfiltered \( v(t) \) curve, despite the filtered curve satisfied criteria referred to in (ii). The mean velocity of this range was computed for both successive gliding phases, as well as the corresponding mean acceleration based upon the acceleration to time curve \( a(t) \). The \( a(t) \) curve (Figure 4) was obtained by numerical differentiation of the filtered \( v(t) \) curve, using the fifth order centered formula:

\[
a_i = \frac{2v_{i-2} - 16v_{i-1} + 16v_{i+1} - 2v_{i+2}}{24 \Delta t}
\]  

An “undulating” pattern of the \( a(t) \) curve (Figure 4) was presented in all cases, and should express small changes in body alignment of the swimmer, as well as the traditional instability of the numerical derivation.

Accelerations to velocity curves, \( a(v) \), were also plotted for all subjects and trials (Figure 5).

Both \( a(t) \) and \( a(v) \) curves showed individual tendencies—probably associated with individual and characteristic body alignments—but displayed consistently smaller acceleration values for the first gliding position. By considering body mass \( m \) as the inertial term of the equation of movement (not taking into account any “added mass” effect), the drag force \( D \) responsible for the acceleration \( a \) was expected to be higher in the second gliding. The drag force was computed using the expression:

![Figure 4 — A illustrative \( a(t) \) curve for both gliding phases, based on which the mean acceleration was calculated.](image)

![Figure 5 — Acceleration to velocity curve—\( a(v) \).](image)
\[ D = m \times a \] (2)

In equation (2) \( a \) represents the mean acceleration for each gliding and swimmer.

To quantify the drag coefficient for each gliding and swimmer, the following equation was used, assuming water density (\( \rho \)) as 1000 kg/m\(^3\):

\[ C_D = \frac{2D}{\rho S v^2} \] (3)

In equation (3) \( v \) stands for the mean velocity for each gliding and swimmer, and \( D \) for the correspondent mean value.

The legitimacy for the use of the Newtonian equation of \( D \) was based upon expected Reynolds numbers (\( Re = \frac{L \rho v}{\eta} \)) above 1000 (2652.8–3360.0 for females and 2901.2–3669.2 for males), assuming a dynamic viscosity of water (\( \eta \)) at 27.5 °C of 0.85 Ns/m\(^2\), \( \rho = 1000 \) kg/m\(^3\), and \( L \) = characteristic length of the body along the direction of flow (body height, or body height + 27% body height, respectively for the first and second gliding positions).

Common measures of central tendency and dispersion, namely mean ± SD, were used for descriptive statistics. Although normality conditions and other assumptions for parametric tests were not violated (Kolmogorov-Smirnov and Shapiro-Wilk), the sample size determined the use of nonparametric statistics (SPSS 16.0). Accordingly, the Mann-Whitney and the Wilcoxon tests were used to compare the variables between gender and within gender groups, respectively. Statistical significance was set at \( \alpha = .05 \), but corrected for multiple comparisons using the Bonferroni correction procedure, which set the real \( \alpha \) level in \( \alpha = .0167 \).

**Results**

The main results of this study are presented in Tables 1 and 2. The first one shows the \( v \) and \( D \) results, while the second one shows \( S \) and \( C_D \) values.

It can be noticed that the mean value of the gliding velocity selected for \( S \) and \( C_D \) assessment were similar between the two gliding positions. As stated in the previous section, this was a methodologically induced result, to allow a better comparison of hydrodynamic parameters.

For the total sample \( S \) and \( C_D \) values were higher for the second gliding position comparing to the first one. Similar tendencies were perceived for the two gender subgroups, but differences were not statistically significant. Also not statistically significant were the differences found between variables for the two genders. Interesting to note was that males tended to have a higher \( D \) value than females in the first position, while females had a greater average \( D \) in the second position. This trend was not great enough to demonstrate statistical significance.

**Discussion**

The absolute values of \( v \) selected in this study (Table 1) were relatively low when compared with other velocity values reported in literature for swimming drag studies, especially passive drag studies. Values around 1.4 m/s, however, were studied in towing situations by a number of authors (Counsilman, 1955; Charbonnier, 1975; Chatterd et al., 1985, 1990a,b; Clarys, 1979; Van Manen & Rijken, 1975, and Miyashita & Tsunoda, 1978; Strojnik et al., 1999). More recently, however, higher velocities were selected by the researchers. For instance, Marinho et al. (2009) modeled the hydrodynamics of both the same gliding positions using CFD at velocities ranging from 1.6 to 2.0 m/s. An even higher range of velocities was experimentally studied by Lyttle et al. (1998): from 1.6 to 3.1 m/s. The relatively low \( v \) values used in this study, apart from being reality based, can be further justified by a number of factors: (i) the necessity to restrict the study to the range of velocities of the second gliding phase; (ii) the relative weight of the female swimmers subgroup in the sample results and (iii) the level of the swimmers tested, all of national level, not international elite, mixing junior and senior swimmers.

**Table 1** Mean ± SD values of the measured gliding velocity (\( v \)), and computed drag force (\( D \)) for the two studied breaststroke gliding positions. Probability (\( p \)) test values for the study of significant differences (\( p ≤ 0.0167 \)) between genders for the same variable and gliding position, and within genders between gliding positions are presented. A separate computation for the total sample (males and females together) was also conducted comparing the two gliding positions.

<table>
<thead>
<tr>
<th>Group</th>
<th>( v_{1,p} ) (m/s)</th>
<th>( v_{2,p} ) (m/s)</th>
<th>( D_{1,p} ) (N)</th>
<th>( D_{2,p} ) (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males, ( N = 6 ) (mean ± SD)</td>
<td>1.39 ± 0.152</td>
<td>1.39 ± 0.152</td>
<td>-34.66 ± 7.869</td>
<td>-42.92 ± 5.658</td>
</tr>
<tr>
<td>( p ) value within males</td>
<td>( p = 1.0000 )</td>
<td></td>
<td>( p = 0.2188 )</td>
<td></td>
</tr>
<tr>
<td>Females, ( N = 6 ) (mean ± SD)</td>
<td>1.36 ± 0.101</td>
<td>1.36 ± 0.101</td>
<td>-28.68 ± 2.816</td>
<td>-49.58 ± 7.474</td>
</tr>
<tr>
<td>( p ) value within females</td>
<td>( p = 1.0000 )</td>
<td></td>
<td>( p = 0.0313 )</td>
<td></td>
</tr>
<tr>
<td>( p ) value males vs. females</td>
<td>( p = 0.8182 )</td>
<td>( p = 0.8182 )</td>
<td>( p = 0.1320 )</td>
<td>( p = 0.1797 )</td>
</tr>
<tr>
<td>Total, males + females (mean ± SD)</td>
<td>1.37 ± 0.124</td>
<td>1.37 ± 0.124</td>
<td>-31.67 ± 6.442</td>
<td>-46.25 ± 7.215*</td>
</tr>
<tr>
<td>( p ) value for the total sample (males + females)</td>
<td>( p = 1.0000 )</td>
<td></td>
<td>( p = 0.0034 )</td>
<td></td>
</tr>
</tbody>
</table>

Note. The subscript \( 1 \) signifies the first glide position and \( 2 \) signifies the second glide position of the breaststroke underwater stroke. Significant differences between gliding positions are given an asterisk: * (\( p ≤ 0.0167 \)).
Drag effects of gliding in breaststroke

Table 2  Individual and mean ± SD values of the cross-sectional area of the body (S), and for the drag coefficient (C_{D}), calculated for the two studied breaststroke gliding positions. Probability (p) test values for the study of significant differences (p < 0.0167) between genders for the same variable and gliding position, and within genders between gliding positions are presented. A separate computation for the total sample (males and females together) was also conducted comparing the two gliding positions.

<table>
<thead>
<tr>
<th>Group</th>
<th>S_{1}^P (cm²)</th>
<th>S_{2}^P (cm²)</th>
<th>CD_{1}^P</th>
<th>CD_{2}^P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males, N = 6 (mean ± SD)</td>
<td>764.19 ± 121.776</td>
<td>810.217 ± 116.021</td>
<td>0.476 ± 0.073</td>
<td>0.605 ± 0.285</td>
</tr>
<tr>
<td>p value within males</td>
<td>p = 0.2188</td>
<td>p = 0.2188</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Females, N = 6 (mean ± SD)</td>
<td>716.66 ± 81.565</td>
<td>758.29 ± 82.180</td>
<td>0.441 ± 0.082</td>
<td>0.723 ± 0.176</td>
</tr>
<tr>
<td>p value within females</td>
<td>p = 0.0313</td>
<td>p = 0.0313</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p value males vs. females</td>
<td>p = 0.9372</td>
<td>p = 0.5887</td>
<td>p = 0.3939</td>
<td>p = 0.2403</td>
</tr>
<tr>
<td>Total (males + females) (mean ± SD)</td>
<td>740.42 ± 101.886</td>
<td>784.25 ± 99.62*</td>
<td>0.458 ± 0.076</td>
<td>0.664 ± 0.234*</td>
</tr>
<tr>
<td>p value for the total sample</td>
<td>p = 0.0122</td>
<td>p = 0.0093</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(males + females)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note. The subscript 1 signifies the first glide position and 2 signifies the second glide position of the breaststroke underwater stroke. Significant differences between gliding positions are given an asterisk: * (p < 0.0167).

D values calculated in this study (Table 1) tended to be lower, although being consistent with previously published passive drag values described for competitive swimmers towed at similar velocities. From the studies previously quoted, D values ranged from 35.3 N for females (Miyashita & Tsunoda, 1978) to 51.9 N for male national-level swimmers (Clarys, 1979). Lyttle et al. (1998), at the lower velocities studied (1.6 m/s), and at the deepest towing position they studied (0.6 m deep), reported values for male swimmers of 58.1 ± 9.3 N, which were higher but coherent with the 36.12 ± 9.54 N observed for a similar gliding position, but deep underwater, and for lower speeds. Moreover, the swimmers of the current study were free to adopt their most streamlined position, once no mechanical constraints were imposed, namely a cable with a handlebar to allow towing, suggesting that a better gliding position can be attained. Interestingly, Klauck & Daniel (1976) previously observed that low drag values tended to be obtained by inverse rather than direct dynamics (towing method), and considered that more accurate hydrodynamic results may be obtained by inverse dynamics without the constraints imposed by a towing apparatus.

No significant differences were found between genders in D values for the two studied gliding positions. Nevertheless, an interesting tendency, not supported by statistical significance, was for females to present lower drag values than males in the second gliding position, while males had lower D values than females in the first position, even disregarding differences in gliding velocity. It is possible to speculate that the “reshaping” effect of the arm position may be quite different among genders, as suggested by the relative differences found in S between the two gliding positions for both genders (Table 2), which will be discussed in future paragraphs. Normally, D values for female swimmers are expected to be lower than for their male counterparts (Chatard et al., 1990b; Kolmogorov & Duplishcheva, 1992; Miyashita & Tsunoda, 1978; Onoprienko, 1967). Nevertheless, Chatard et al. (1990a,b), for instance, found lower values for males than females of lower competitive level, and the opposite for the higher proficiency groups.

D force was found to be lower for the first gliding position of the breaststroke underwater cycle, probably due to a parallel and concurrent effect of S and C_{D}. The increased body length and slenderness associated with the flexed shoulders and extended position of the arms along the longitudinal axis of the body may reduce C_{D}, as well as may have an effect upon the reduction of S. Similar to the D values — and in accordance with the information previously referred to — for the total sample S was significantly higher in the second gliding position than in the first one. This fact could be explained by the “compressive” effect over the shoulders and chest width produced by the flexed shoulders, especially expectable in the female group, and may be one of the main determining factors associated with a reduced drag in the first gliding position. It is important to state that S values measured in this study are in close agreement with previous reported results of Clarys (1979) using a similar method: 0.077 ± 0.012 m². Toussaint et al. (1988) also used planimetry to assess S values, reporting slightly higher results (0.091 ± 0.009 m² and 0.075 ± 0.008 m², respectively for males and females), but in accordance with sample differences in height (1.81 ± 0.07 m and 1.77 ± 0.06 m). The S values we measured may differ from the actual gliding S values, once it is possible that the gliding alignment of the body may differ from the standing position. In fact, we must assume that it is possible that some swimmers may adopt, at least in some instants during the glide, an inclined body position with respect to the gliding direction. Our observation of the recorded video images revealed some
inclined gliding directions with respect to the horizontal, but showing a proper body alignment regarding that gliding direction; we didn’t noticed any inclined body position regarding the direction of motion that would change $S$ values. Moreover, the expected effect of possible small changes in body alignment upon $S$ values, and calculated $C_D$ values, will certainly be smaller than those obtained during active front crawl swimming, as used by Toussaint et al. (1988). In the same perspective, we are convinced that this approach is also more accurate for $S$ and $C_D$ assessment than calculating active drag front crawl $C_D$ values using a constant estimation of $S$ based upon body volume powered 2/3 (Kolmogorov & Duplischeva, 1992).

Also, $C_D$ values were similar to previously available results obtained from experimental (Clarys, 1979), as well as from numerical approaches (Marinho et al., 2009). They were also similar to those reported for front crawl swimming active drag considering $S$ constant (Toussaint et al., 1988; Kolmogorov & Duplischeva, 1992). For the total sample, the $C_D$ values were significantly higher in the second gliding position than in the first one. This was consistent with the observed increase of $S$ and $D$. These results are in agreement with those reported earlier by Marinho et al. (2009); our $C_D$ values were slightly lower than those reported by the authors, and computed for also lower velocity values. Consistently, Marinho et al. (2009) also reported a reduction of $C_D$ with the gliding velocity. So, this finding confirms our initial hypothesis: the first gliding position corresponds to an elongated body position that allows a reduction of passive drag both reducing $S$ and $C_D$. This may be explained by the differences in body shape and length, determining a higher slenderness (Vogel, 1994). Chatard et al. (1990b) observed that passive $D$ grows with the ratio of body mass to body height ($r = .93$), something that may be assumed as a kind of inverse slenderness index. With data from the current study, we observed similar body mass to height ratios for male and female swimmers (respectively 0.36 and 0.35 kg/cm) and did not find any significant correlation between this variable and $D$ values for males, females or the total sample (0.044 < $r$ < 0.064). This suggests that body shape can play a more important role as a determinant of $C_D$ than slenderness.

As a concluding remark, it can be stated that, according with previous numerical approaches (Marinho et al., 2009), it was possible to emphasize in this paper that, for breaststroke starts and turns, the first gliding position is, in general, more hydrodynamic than the second one, allowing lower $S$, $C_D$, and $D$ values for the same range of speeds. As a practical consequence, swimmers and coaches should emphasize the time spent during the first gliding phase after starts and turns, instead of the second one. They should also stress the need for body position control during its execution, particularly during the more resistive second glide. These results also pointed out the need for technical evaluation, control and advice to allow drag reductions during swimming performance, and not only emphasizing propulsion increase possibilities.

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**References**


