Hydrodynamic Characteristics of Competitive Swimmers of Different Genders and Performance Levels

Sergei V. Kolmogorov, Olga A. Rumyantseva, Brian J. Gordon, and Jane M. Cappaert

The purpose of this study was to describe the hydrodynamic characteristics of the four strokes by gender and performance level. Active drag during maximal swimming was measured in each of the four swimming strokes (freestyle, butterfly, backstroke, and breaststroke) on males and females of varying ability levels using the perturbation method developed by Kolmogorov and Duplisheva (1992). Active drag \( (F_{DN}) \), the hydrodynamic coefficient \( (C_x) \), and total external mechanical power output \( (P_{to}) \) were calculated at each swimmer’s maximal swimming velocity. There were complex, non-linear relationships between maximum swimming velocity and the three hydrodynamic indicators. The four swimming strokes were ranked in order of resistance based on the three hydrodynamic indicators. The order, from least to most resistance, was (1) freestyle, (2) backstroke, butterfly, (3) breaststroke. No statistical difference was seen between the backstroke and butterfly. Within each stroke, the most important factor for reducing active drag appeared to be individual biomechanical technique.

The controversy of active and passive drag in swimming has been discussed in the literature for many years. Passive drag is the amount of water resistance that a human body experiences in an unchanging posture, while active drag is the water resistance associated with the swimming motion. Passive drag has been measured by towing swimmers through the water in a prone position (Clarys, Jiskoot, Rijken, & Brouwer, 1974; Counsilman, 1955). The passive drag from the water was well approximated by the general fluid force equation for passive or active drag situations:

\[
FD = \frac{1}{2} C_x \cdot \rho \cdot S \cdot V^2
\]  

where \( F_D \) is the active or passive drag force, \( C_x \) is the hydrodynamic coefficient, \( \rho \) is the density of water, \( S \) represents the frontal surface area of the swimmer, and \( V \) is towing velocity. Body size and shape were shown to influence passive drag but not active drag (Clarys, 1979). These findings led Clarys (1979) to conclude that body shape and composition do not influence active drag, but rather changes in shape (i.e., biomechanical swimming technique) were the main influence on drag. Therefore, low or high active drag...
during swimming must be determined by correct or incorrect swimming technique (Clarys, 1979).

Active drag during human swimming has been experimentally determined by many (Clarys, 1979; Di Prampero, Pendergast, Wilson, & Rennie, 1974; Hollander et al., 1986; Kolmogorov & Duplesheva, 1992; Pendergast, Di Prampero, Craig, Wilson, & Rennie, 1977; Rennie, Pendergast, & Di Prampero, 1975; Toussaint et al., 1988a). Early measurements involved indirect calculations of active drag based upon changes in oxygen consumption with additional drag loaded onto the swimmer (Clarys, 1979; Di Prampero et al., 1974; Pendergast et al., 1977; Rennie et al., 1975). The results of these early studies indicated that active drag was much higher than passive drag. More recently, the Measuring Active Drag (MAD) system was used to directly measure active drag. Active drag values during the freestyle stroke were found to be similar to passive drag and were lower than previously reported values obtained through indirect methods (Hollander et al., 1986; Van der Vaart et al., 1987). Using the MAD system, Toussaint et al. (1988a) found active drag of an Olympic champion to be much lower than that of an average-level swimmer through a range of velocities. With the most recent method of measuring active drag during swimming, a velocity perturbation method, active drag was shown to vary from 50% to 150% of passive drag values at maximal swimming velocity (Kolmogorov & Duplesheva, 1992). The results of this study supported the conclusion of Clarys (1979) and the data of Toussaint et al. (1988a) that elite swimmers have lower active drag than average-level swimmers due to better technique (Kolmogorov & Duplesheva, 1992).

The above-mentioned research on the magnitude of active drag and its relationship to passive drag remains controversial. There is agreement that reducing active drag is important in swimming and that correct swimming technique lowers active drag. However, much of the research has focused on the freestyle and little is known regarding the active hydrodynamic coefficient ($C_{Da}$). Therefore, the primary purpose of this study was to describe the magnitudes of active drag ($F_{Da}$), $C_{Da}$, and power output ($P_{to}$) in the four swimming strokes for athletes of different performance levels, genders, and ages at maximal swimming velocities.

**Methods**

**Subjects**

This research was conducted over a 5-year period leading up to the 1992 Olympic Games in Barcelona. The subjects included 310 females and 487 males ranging in age from 10 to 28 years. These subjects represented all performance levels from beginning to elite swimmers. Subjects swam one stroke with the exception of the individual medley swimmers, who swam all four strokes. The numbers of subjects per stroke were as follows: freestyle, 302 females, 481 males; butterfly, 117 females, 220 males; backstroke, 114 females, 204 males; and breaststroke, 171 females, 178 males. All subjects and/or their guardians were familiar with the experiment and voluntarily agreed to participate in the study.

**Active Swimming Measurements**

Hydrodynamic characteristics of the subjects while swimming at their maximal velocity were determined by the perturbation method described by Kolmogorov and Duplesheva (1992). This method changes maximal swimming velocity using added drag provided by a hydrodynamic body (Kolmogorov & Duplesheva, 1992; Kolmogorov, Rumyantseva, & Koygerov, 1991). Using this method, subjects performed two maximal 30 m trials over
which average velocity was calculated. The first trial was free swimming. During the second trial, the swimmer towed (3.5–4.5 body lengths behind) a hydrodynamic body. The hydrodynamic body consisted of a small cylinder filled with water attached to the bottom of a floating board. The hydrodynamic properties of the hydrodynamic body were calibrated previously, allowing us to calculate the drag force due to the body at any velocity.

Active drag and $C_{D_a}$ were calculated using the assumption of equal power output in both trials:

$$F_{D_{a1}} \cdot V_1 = F_{D_{a2}} \cdot V_2$$

where $F_{D_{a1}}$ is the active drag during the first swim, $F_{D_{a2}}$ is the active drag plus the added resistance of the hydrodynamic body, and $V_1$ and $V_2$ are the average 30 m velocities of the first swim and second swim, respectively. Using Equation 1, we expanded the power output from Equation 2:

$$\frac{1}{2} C_{D_a} \cdot \rho \cdot S \cdot V_1^3 = \frac{1}{2} C_{D_a} \cdot \rho \cdot S \cdot V_2^3 + F_b \cdot V_2$$

where $F_b$ represents the added drag due to the hydrodynamic body. Solving for the active hydrodynamic coefficient yields

$$C_{D_a} = \frac{F_b \cdot V_2}{\frac{1}{2} \rho \cdot S \cdot (V_1^3 - V_2^3)}.$$  

Substituting $C_{D_a}$ in Equation 1 during the first maximal swim gives the active drag ($F_{D_a}$):

$$F_{D_a} = \frac{F_b \cdot V_2 \cdot V_2^2}{V_1^3 - V_2^3}.$$  

Power output was calculated by multiplying $F_{D_a}$ and the maximal velocity. This method has been shown to be reliable, and $F_{D_a}$ measurements have been verified with a maximum potential error of 6–8% (Kolmogorov & Duplisheva, 1992).

**Passive Towing Measurements**

Passive hydrodynamic characteristics were measured in a pool using a pulley system and varying weights. Swimmers were attached to the weight system with a belt. Swimmers assumed a streamlined position (prone) and successive weights were dropped, towing the swimmer through the water. The velocity value was recorded once it was measured to be constant. Frontal surface area was estimated using human body volume to the 2/3 power (Kolmogorov & Duplisheva, 1992), and the passive hydrodynamic coefficient ($C_{D_p}$) was calculated using Equation 1.

**Data Analysis**

Data for all subjects were grouped by gender to describe the hydrodynamic indicators $F_{D_a}$, $C_{D_a}$, and $P_{to}$ over a large velocity range. These indicators were averaged within each 0.1 m/s velocity interval (for example, 1.0–1.1 m/s). Each velocity range contained at least 10 swimmers except in the men’s freestyle interval, 2.0–2.1 m/s, in which there were 7 swimmers. Within each gender, $C_{D_a}$ was compared (ANOVA) between the strokes at the same absolute velocity. Within each stroke, $C_{D_a}$ was compared between genders at the same absolute velocity. Only $C_{D_a}$ was chosen for the comparison since it was the most objec-
tive hydrodynamic indicator. The relationship between active and passive data parameters was assessed using correlations. The statistical significance level was set at $p < .05$.

**Results**

Within each stroke, there were large variations in the values of the hydrodynamic indicators $F_{Da}$, $Cx_{Da}$, and $Pto$ for the same maximum swimming velocity ($V$) (Figures 1 and 2). A comparison of the $Cx_{Da}$ values between female and male swimmers within each stroke revealed no statistical differences throughout the entire range of compared absolute velocities.

The indicators of passive drag, $F_{Dp}$ and $Cx_{Dp}$, depended entirely on velocity and were well estimated by Equation 1. The coefficients $Cx_{Da}$ and $Cx_{Dp}$ did not correlate with each other ($r = -.09$). $Cx_{Da}$ had a strong relationship ($r = .98$) with $F_{Da}/F_{Dp}$. In the breaststroke, $F_{Da}$ always exceeded $F_{Dp}$.

In female subjects, statistical differences in $Cx_{Da}$ were found between the strokes (Figure 1). The $Cx_{Da}$ for freestyle was lower than that for the butterfly starting at the 1.3–1.4 ms$^{-1}$ velocity range and continuing throughout the range of velocities. Freestyle $Cx_{Da}$ was lower than that for the backstroke beginning at the 1.2–1.3 ms$^{-1}$ range. This difference continued through the range of velocities. Statistical differences between $Cx_{Da}$ in the breaststroke and in both the butterfly and backstroke were observed beginning at the 0.9–1.0 ms$^{-1}$ range and continued through maximal $V$. $Cx_{Da}$ for the butterfly and backstroke was not statistically different at any of the swimming velocities.

In the male subjects, a statistical difference between the magnitudes of $Cx_{Da}$ in the freestyle and the butterfly was observed starting at the 1.3–1.4 ms$^{-1}$ range and continued over the entire velocity range (Figure 2). $Cx_{Da}$ in the freestyle was lower than in the backstroke at the 1.3–1.4 ms$^{-1}$ range through the 1.6–1.7 ms$^{-1}$ range and lower than $Cx_{Da}$ in the breaststroke starting at the 0.9–1.0 ms$^{-1}$ velocity range. The magnitude of $Cx_{Da}$ in the breaststroke was statistically higher than in the butterfly starting at the 0.9–1.0 ms$^{-1}$ range and higher than the backstroke starting at the 1.1–1.2 ms$^{-1}$ velocity range. There was no statistical difference between $Cx_{Da}$ in the butterfly and the backstroke throughout the entire range of swimming velocities.

**Discussion**

There were complex nonlinear relationships between maximum $V$ and each of the hydrodynamic indicators $F_{Da}$, $Cx_{Da}$, and $Pto$ in all four strokes (Figures 1 and 2). According to $F_{Da}$, $Cx_{Da}$, and $Pto$, the swimming strokes were ranked in terms of resistance. The ranking, in order from low to high resistance, was (1) freestyle, (2) backstroke, butterfly, and (3) breaststroke. These stroke rankings could only be made at the higher testing velocities. At low velocities, representing beginning swimmers, there was no statistical difference between the strokes and $Cx_{Da}$. With the exception of the butterfly, this order of resistance is in general agreement with measured metabolic energy expenditure for each swimming stroke (Holmer, 1992). A possible explanation for a higher measured metabolic cost of the butterfly (Holmer, 1992) than the $F_{Da}$, $Cx_{Da}$, and $Pto$ values might predict may be a function of the skill level required to successfully execute the butterfly in comparison to the breaststroke.

**Relationship Between Swimming Velocity and Active Drag ($F_{Da}$)**

The magnitudes of $F_{Da}$ for the men’s freestyle were much lower than those predicted previously via indirect methods (Clarys, 1979; Di Prampero et al., 1974; Pendergast et al., 1977; Rennie et al., 1975). They were also lower than the values measured on the MAD...
Figure 1 — Experimental relationships between $V$ (ms$^{-1}$), $F_{Da}$ (N), $C_{Da}$, and $Pto$ (W) in athletic styles of swimming for female subjects (mean and SE). ○ freestyle, ■ butterfly, △ backstroke, □ breaststroke.
Figure 2 — Experimental relationships between $V$ (ms$^{-1}$), $F_{da}$ (N), $C_{xda}$, and $Pto$ (W) in athletic styles of swimming for male subjects (mean and SE). ◯ freestyle, ■ butterfly, △ backstroke, □ breaststroke.
system (at 1.5 ms\(^{-1}\), Van der Vaart et al., 1987 = 53.2 ± 5.9 N, current study = 28.0 ± 5.9 N; in the 1.50–1.60 ms\(^{-1}\) velocity range, Hollander et al., 1986 = 66.3 ± 4.1 N, current study = 43.2 ± 15.9 N). The differences between the active drag values may have been due to the levels of athletes studied or the differences in efforts required for each study (maximal vs. more submaximal).

A comparative analysis of the magnitudes of \(F_{Da}\) at high velocities in the women’s breaststroke, men’s freestyle, and butterfly showed a trend for horizontal or even downward movement (Figures 1 and 2). At the time of testing, the athletes performing the aforementioned swimming strokes were the highest ranked in the world. At the same time, according to the magnitudes of \(F_{Dp}\), these athletes did not differ from other elite swimmers. Consequently, we believe that these elite swimmers displayed biomechanically proficient swimming techniques which were characterized by low \(F_{Da}\) at maximum \(V\). This experimental relationship supports the hypothesis expressed previously by Clarys (1979) that the amount of active drag is related to biomechanical technique.

**Considerations Regarding the Dimensionless Hydrodynamic Coefficient (\(C_{x_Da}\))**

The literature provides data on the hydrodynamic coefficient obtained under conditions of passive motion (\(C_{xDp}\)) but there is no information regarding \(C_{xDa}\). An analysis of Equation 1 shows that the magnitude of \(F_{Da}\) depends on the water density, the characteristic hydrodynamic size of the swimmer’s body, the swimmer’s movement velocity squared, and the dimensionless hydrodynamic coefficient.

There were no significant differences between females’ and males’ values of \(C_{xDa}\) at any of the compared absolute velocities. This supports the idea that the most important effect on hydrodynamic efficiency is proper stroke technique. It has been speculated that women have a lower \(F_{Da}\) and therefore lower \(C_{xDa}\) than men because they can maintain a more horizontal body position due to body composition differences (McLean & Hinrichs, 1995; Pendergast et al., 1977). However, our data did not support this concept. Instead our results were in agreement with the idea of Clarys (1979) that stroke technique is more important in reducing active drag than body composition.

In passive towing, \(C_{xDp}\) depends on the shape of the swimmer’s body (i.e., physical build), features of the skin and hair, and body streamlining (Gordon, Dmitriev, & Chebotareva, 1985). In active swimming, \(C_{xDa}\) quantitatively reflects the interaction of different parts of the swimmer’s body with the passing flow of fluid. In other words, \(C_{xDa}\) depends on the biomechanical swimming technique (Kolmogorov & Duplicheva, 1992). Consequently, the dimensionless \(C_{xDa}\), determined under natural swimming conditions, is an integral quantitative indicator of the swimmer’s technical ability and level (Kolmogorov & Duplicheva, 1989; Kolmogorov, Turetski, Koigerov, & Rumyantseva, 1991).

The nonlinear, complex relationship between \(V\) and \(C_{xDa}\) seemed to reflect the interaction of two opposite processes observed as the age and skill level of the athletes increased. On the one hand, with the increase in \(V\) there is an increase in degree of turbulent flow of water passing the swimmer’s body that facilitates the increase in \(C_{xDa}\) (Papanastasiou, 1994). On the other hand, the improvement in a swimmer’s biomechanical technique lowers \(C_{xDa}\) under conditions of limited energy input (Granit, 1970).

In the initial range of velocities, the freestyle, butterfly, backstroke, and breaststroke for male and female subjects showed periods of decrease and subsequent relative stabilization of \(C_{xDa}\) (Figures 1 and 2). This supports the idea of increased biomechanical technique proficiency as the swimming strokes are learned and mastered. These experi-
mental results explained the fairly large increase in $V$ with a small increase in $F_{Da}$ in the initial range of velocities (for example, in the men’s freestyle, $V$ increases by 0.3 ms$^{-1}$ with only a 10.7 N increase in $F_{Da}$).

In the range of higher swimming velocities, $C_{x_{Da}}$ increased in all strokes and ended in a phase of relative stabilization or slight decrease. It seems that starting from a specific swimming velocity, the increase in $C_{x_{Da}}$ was connected to the negative effect of increased turbulence predominating over biomechanically proficient swimming technique. Such critical velocities in female subjects were as follows: freestyle at 1.35 ms$^{-1}$, butterfly at 1.26 ms$^{-1}$, backstroke at 1.17 ms$^{-1}$, and breaststroke at 0.95 ms$^{-1}$. The critical velocities in male subjects were somewhat higher: freestyle at 1.42 ms$^{-1}$, butterfly at 1.26 ms$^{-1}$, backstroke at 1.26 ms$^{-1}$, and breaststroke at 1.15 ms$^{-1}$.

The $C_{x_{Da}}$ in the women’s breaststroke (Figure 1) and men’s freestyle and butterfly (Figure 2) at maximum velocity was in agreement with $F_{Da}$ values. It seems that a high level of technical ability is mandatory for achieving a leading position in world swimming. Again, in terms of $C_{x_{Da}}$, these athletes did not differ from other elite swimmers.

**Relationship Between Swimming Velocity and Total External Mechanical Power ($P_{to}$)**

An analysis of $P_{to}$ values in the women’s breaststroke and men’s freestyle and backstroke at maximum velocity revealed that elite swimmers were able to raise the maximum swimming velocity with a parallel slight increase in $P_{to}$ or even its reduction (in women’s breaststroke) (Figures 1 and 2). This could be an advantage to those elite swimmers. Under conditions of limited input of metabolic energy, swimmers with high $P_{to}$ would be unable to maintain the high swimming velocity over the entire distance of the competition, even with metabolic capabilities identical to swimmers who require lower $P_{to}$ values to swim the same velocity.

The mechanism of observed $P_{to}$ differences in athletes has been discussed by Toussaint et al. (1988b) using the concept of propelling efficiency ($e_p$). Elite-level athletes have been shown to have a higher $e_p$ than lower level athletes (Cappaert, Pease, & Troup, 1995; Toussaint, 1990). A mathematical definition of propelling efficiency (Alexander, 1968; Toussaint et al., 1988b; Webb, 1971) yields

\[
e_p = \frac{P_{uo}}{P_{uo} + P1 + P2}
\]

where $P_{uo}$ is the external mechanical power expended to overcome $F_{Da}$; $P1$ is the power expended on applying an impulse to a specific mass of water, directed forward and necessary for creating propulsive force; and $P2$ is the power expended on forming the turbulent eddies when the arms and legs interact with the flow. In our case $P_{uo} + P1 + P2 = P_{to}$. The increase in $e_p$ occurs as a result of decreasing $P1$ and $P2$ by improving biomechanical technique (Toussaint et al., 1988b). This in turn decreases $P_{to}$ for a given $V$.

**Summary**

The active hydrodynamic characteristics of swimming humans were different than passive hydrodynamics. In all swimming strokes at the maximum absolute velocity, men experienced greater $F_{Da}$ as well as much greater $P_{to}$ (virtually twice as much) than women. However, there was no significant difference between men and women in $C_{x_{Da}}$, the most...
objective of the three hydrodynamic indicators, when compared at the same absolute velocities within each stroke.

Swimming strokes according to maximum velocity were rated from fast to slow: freestyle, butterfly, backstroke, breaststroke. At the same time, according to the hydrodynamic indicators $F_{Da}$, $C_{Da}$, and $Pto$, in men and women the swimming strokes were ranked as follows (in order of increasing resistance): (1) freestyle, (2) backstroke, butterfly, (3) breaststroke. Within genders, statistical differences in the indicator $C_{Da}$ existed between the strokes in most cases except between the butterfly and the backstroke.

The results supported the idea that elite swimmers have a higher ability to reduce active drag than nonelite swimmers. We believe that elite athletes reduced active drag through superior stroke technique as evidenced by a leveling off of $F_{Da}$ and $C_{Da}$ at the high velocity ranges. Although specific technique characteristics were not identified, this study supported the idea of Clarys (1979) that active drag is highly dependent upon biomechanical swimming technique.

References


