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ORIGINAL ARTICLE

Active and passive drag: the role of trunk incline

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Abstract The aim of this study was to investigate the role of trunk incline (TI) and projected frontal area (A_{eff}) in determining drag during active/passive measurements. Active drag (D_a) was measured in competitive swimmers at speeds from 0.6 to 1.4 m s^{-1}; speed specific drag (D_a/v^2) was found to decrease as a function of v ($P < 0.001$) to indicate that the human body becomes more streamlined with increasing speed. Indeed, both A_{eff} and TI were found to decrease with v ($P < 0.001$) whereas C_d (the drag coefficient) was found to be unaffected by v. These data suggest that speed specific drag depend essentially on A_{eff}. Additional data indicate that A_{eff} is larger during front crawl swimming than during passive towing (0.4 vs. 0.24 m^2). This suggest that D_a/v^2 is larger than D_p/v^2 and, at a given speed, that D_a is larger than D_p.

Keywords Swimming · Hydrodynamic resistance · Projected frontal area · Drag coefficient

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Introduction

Water resistance or drag (D, N) is defined as “the force on an object moving in a fluid due to the rate of change in momentum of the fluid influenced by the object moving through the fluid” (Vogel 1994). Drag is a major determinant of the energy cost of swimming (C) at a specific velocity, as shown by the following equation:

$$C = (W_d/\eta_P)\eta_O^{-1} \quad (1)$$

where C represents the energy expended to cover one unit distance at a given speed (generally expressed in J m^{-1}), η_P and η_O are the propelling and the overall efficiencies, respectively, and W_d (J m^{-1}) is the work spent per unit of distance to overcome hydrodynamic resistance (i.e. D, N) (e.g. Zamparo 2006). Therefore, for any given speed: $D = W_d$ (J m^{-1} = N).

Determination of drag during swimming (D_a, active drag) is therefore a key issue in evaluating swimming performance. However, whereas the hydrodynamic resistance determined by towing a non-swimming subject through the water (passive drag, D_p) has been investigated for more than a century, the direct determination of active drag has not been performed yet, even if several methods to estimate it have been described in the literature (for a review see Wilson and Thorp 2003).

For instance, estimated D_a has been reported to be two to three times larger than D_p (e.g. di Prampero et al. 1974), but also to be equal or less than D_p (Kolmogorov and Duplisheva 1992; Toussaint et al. 1988). In the former case, the difference between the D_a and D_p values was attributed to the fact that (1) passive drag does not take into account the drag created by the movements of the swimmer to provide the thrust and that (2) during swimming the body is less streamlined and presents a greater frontal area

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to the fluid. In the latter case, the lack of difference between D_a and D_p was attributed to the fact that the arm strokes (and the leg kicks) result in the body being lifted in water, thus presenting a lesser frontal area to the flow than when the body was passively towed at the same speed (see Wilson and Thorp 2003).

Therefore, the role of frontal area in determining hydrodynamic resistance is a key issue for understanding/improving swimming performance. However, none of these studies (and others about this topic) has attempted so far (at least to our knowledge) to investigate whether the differences in active and passive drag could indeed be attributed to differences in frontal area.

It must be pointed out that frontal area is not the unique factor to be accounted for. Swimming technique has an influence on hydrodynamic resistance too: lateral body movements or excessive kicking movements may reduce the streamline of the body and increase drag; as a matter of fact, it was shown that effective training decreases the hydrodynamic resistance, even in elite swimmers (e.g. Termin and Pendergast 2001; Pendergast et al. 2005). It has also been hypothesized that elite swimmers might be able to generate a vortex with their hands, which would help the body to better slip through the water, thus lowering D_a (e.g. Arellano et al. 2006). Swimming performance seems also to be related with passive drag differences among subjects, thus explaining the different abilities during the gliding phases of the race (Chatard et al. 1990a, b).

Hydrodynamic resistance has three components: friction drag (D_f), pressure (or form) drag (D_{pr}) and wave drag (D_w). Studies of passive drag indicate that pressure drag is the major determinant of D_p accounting for 74, 55 and 51% at 1.0, 2.0 and 2.2 m s^{-1}, respectively; whereas friction (24, 25, 23%) and wave (2, 20, 26%) drag have a lower influence on D_p at the corresponding speeds (Pendergast et al. 2005). Even if other authors have found different contributions of D_f, D_w and D_{pr} to total drag (e.g. Vorontsov and Rumyantsev 2000; Vennel et al. 2006), D_{pr} can indeed be considered a major determinant of D_p at moderate swimming speeds (below 1.4 m s^{-1} see Wilson and Thorp 2003). D_{pr} is given by:

$$D_{pr} = {}^{1}\!/_{2}\rho C_d A_{eff} v^2 \tag{2}$$

where A_{eff} is projected frontal area, C_d is the coefficient of hydrodynamic resistance, ρ is water density and v is the swimming speed.

According to Vogel (1994), it is possible to investigate whether a body in water changes "configuration" with speed by plotting the drag over velocity (v) squared (the speed specific drag: D/v^2) against v. If D/v^2 is a negative function of v, it means that the object has a relatively lower drag at high speeds; on the other hand, if the line ascends this implies that the body has a disproportionate drag at high speeds.

Since, at speeds lower than 1.4 m s^{-1} D_{pr} is the major determinant of drag ($D \approx D_{pr}$), we can also state that:

$$D/v^2 \approx {}^{1}\!/_{2}\rho C_d A_{eff}. \tag{3}$$

According to Eq. 3, assuming a constant value of ρ (997 kg m^{-3} at 25°C), the ratio D/v^2 depends only on the product C_d A_{eff}. Thus, a horizontal D/v^2 versus v relationship suggests that the product C_d A_{eff} is unchanged at different speeds, a descending one indicates that the product C_d A_{eff} decreases with v and an ascending one that the product C_d A_{eff} increases with speed.

Drag coefficient (C_d) is by definition proportional to D/v^2 (Vogel 1994); hence, the changes of D/v^2 with the speed can be expected to mirror changes of C_d with v. On the other hand, the body tends to assume a more streamlined position in water with increasing speed due to the hydrostatic lift (e.g. Lavoie and Montpetit 1986; Vorontsov and Rumyantsev 2000), thus changes of D/v^2 with the speed can be expected to mirror changes of A_{eff} with v too.

The study of the D/v^2 versus v relationship along with an analysis of how A_{eff} changes with increasing speed, can therefore allow to investigate the interplay between C_d and A_{eff} in determining hydrodynamic resistance in the range of speeds usually attained during human swimming. Should C_d result relatively constant over the range of the investigating speeds, the changes in D/v^2 would be mainly due to changes of A_{eff} and hence:

$$D/v^2 \approx kA_{eff}. \tag{4}$$

In this case, the ratio D_a/v^2 (during actual swimming) could be estimated: (1) on the basis of the D_p/v^2 ratio (assessed during passive towing); and (2) of the difference in effective frontal area between the two conditions (A_{eff} a: projected frontal area during swimming; A_{eff} p: projected frontal area during passive towing):

$$D_a/v^2 = D_p/v^2(A_{eff}\text{a}/A_{eff}\text{p}). \tag{5}$$

In this case active drag could finally be calculated, at any given speed, by multiplying the ratio D_a/v^2 times the square of the speed of interest.

The aims of this study therefore were:

1. to investigate the relationship between D/v^2 and v in competitive swimmers over a broad range of swimming speeds (i.e. to assess whether the body changes "configuration" with increasing speed);
2. to investigate whether the changes in the speed specific drag (D/v^2) are related to changes in trunk incline (TI) (and hence in A_{eff}) or in C_d;

3. to investigate whether projected frontal area is the same during passive drag measurements and actual swimming;
4. to estimate active drag based on data of passive drag (measured while the swimmers are towed at constant velocity at the surface) and of A_{eff};
5. to compare estimated active drag values with data of active drag obtained in subjects of comparable age, sex and body built.

Materials and methods

Group A

Data collected in a recent study (Zamparo et al. 2005) on 6 elite college US swimmers where utilized, and partially re-analyzed, to investigate the relationships relating TI, A_{eff}, D/v^2 and C_d with the speed during active drag measurements. The anthropometric characteristics of these subjects are presented in Table 1 (Group A).

Active drag

On these subjects active drag was measured as indicated by di Prampero et al. (1974) and Zamparo et al. (2005) while swimming by kicking the legs only (*L*) at speeds of 0.6, 0.7, 0.8, 0.9 and 1.0 m s^{-1} and while swimming the front crawl (AL) at speeds of 1.0, 1.1, 1.2, 1.3 and 1.4 m s^{-1}. Briefly, the subjects swam in an annular pool and were paced by a platform moving at constant speed above the swimmer's path. Known masses were attached to the swimmer by means of a rope which passed through a system of pulleys fixed to the platform in front of him, thus allowing the force to act horizontally along the direction of movement. This force (*F*) facilitates the swimmer's progression in water by pulling the subject forward and, at constant speed, it is associated with a consequent reduction of $\dot{V}O_2$. The energy required to overcome hydrodynamic resistance (D_a) becomes zero when *F* and D_a are equal and opposite. The swimmer's D_a was estimated, at any given speed and condition, by back-extrapolating the $\dot{V}O_2$ versus *F* relationship to resting $\dot{V}O_2$.

Trunk incline

Trunk incline (TI, also identified as the angle of attack) was assessed when the subject's were swimming freely (without any added load). Video recordings (Handy Cam Vision, Sony, Japan) were taken at a sampling rate of 50 Hz while the subjects passed in front of an underwater window. After the experiments the data were downloaded to a PC and digitized using a commercial software package (Peak Motus, USA). TI (α), in the *L* condition, was calculated as the average value (over one cycle) of the angle between the shoulder (acromion process) and the hip (great trochanter) segment and the horizontal. Black tape markers were applied on these anatomical landmarks to facilitate the digitizing process. In the AL condition this measurement was taken at the end of the in-sweep (when the hand is directly below the shoulder) since in this position the rotation around the sagittal axis is the least and has the smaller influence on the degree of rotation (see also Kjendlie et al. 2004).

Projected frontal area

The projected frontal area (A_{eff}, m^2) was estimated as proposed by Mollendorf et al. (2004) using the following equation:

$$A_{eff} = A_f \cos\alpha + (BSA/2)\sin\alpha \quad (6)$$

where A_f is the frontal area when the swimmer is horizontal ($\alpha = 0$) and BSA is his/her body surface area. In turn: (1) BSA (m^2) was computed as proposed by Shuter and Aslani (2000) from measures of body mass (BM) and body height (BH): $BSA = BM^{0.441} \times BH^{0.655} \times 0.00949$ and (2) A_f was calculated as proposed by Clarys (1979): $A_f = 6.9256 \times BM + 3.5043 \times BH - 377.156$.

Group B

Experiments were performed on 25 subjects (14 male and 11 female swimmers) whose main anthropometric characteristics are reported in Table 1 (Group B). In these subjects we have investigated the relationships relating TI, A_{eff}, D/v^2 and C_d with the swimming speed during passive

Table 1 Anthropometric characteristics of the subjects

Group	M/F	N	Age (years)	Stature (m)	Body mass (kg)	A_f (m^2)	BSA (m^2)	*t* (s)
A	M	6	20.0 ± 1.3	1.79 ± 0.08	71.1 ± 7.9	0.074 ± 0.008	1.86 ± 0.13	46.8 ± 0.9
B	M	14	23.9 ± 2.4	1.78 ± 0.04	69.6 ± 6.4	0.073 ± 0.005	1.83 ± 0.08	59.0 ± 5.7
	F	11	22.5 ± 2.2	1.68 ± 0.05	62.2 ± 7.5	0.064 ± 0.006	1.70 ± 0.10	67.3 ± 6.6

Values are mean ± 1 SD

N number of subjects, *M* males, *F* females, A_f frontal area, *BSA* body surface area, *t* best performance time over the 100 m distance (front crawl) drag measurements; moreover on these subjects we attempted to estimate D_a from measures of D_p (see Eq. 5). The subjects were informed about the methods and aims of the study and gave their written informed consent to participate. The experimental protocol was approved by the Institutional Review Board.

Passive drag

The swimmers were towed passively (at speeds of 0.8, 1.0, 1.2, 1.4, 1.6 and 1.8 m s^{-1}) at the water surface in a 25 m pool. They were linked via a non-elastic wire to a low voltage isokinetic engine (Ben Hur, ApLAb, Italy) positioned at the edge of the pool. The subjects were asked to adopt a prone position with the arms completely flexed at the shoulders and extended at the elbows and wrist, to position the upper arms in contact with the sides of the head (one hand on top of the other), to maintain the feet together with the ankles plantar flexed, to hold onto the wire and to hold their breath after a maximal inspiration. The engine rolled up the wire at a constant speed and the resistance force was measured by a dynamometer (Ben Hur, ApLAb, Italy) that was calibrated before each experimental session. After the experiments the data were downloaded to a PC and further analyzed by means of a dedicated software (DAQ, ApLab, Italy). Average force and speed were calculated between the 10th and 20th meter from the start, i.e. after they have attained constant values. Each swimmer performed the test several times to become familiar with the applied procedures and to find the better gliding position: the last trial was retained for further analysis.

Swimming trials

The subjects were asked to swim the front crawl at four different swimming speeds (ranging from 1 to 1.6 m s^{-1}). They were asked to start without diving from the starting block and to maintain a constant swimming speed (self selected as slow, moderate, fast and maximal). The actual speed was calculated by means of a stopwatch from the time needed to cover 10 m (between the 10th and 20th meter from the start).

Video records

During the experiments (passive drag measurements and swimming trials) video records were taken, with a sampling rate of 50 Hz, by means of a video-camera (Sony Hyper Had, TS-6021PSC, Japan) positioned about 0.5 m below the water surface, perpendicular to the swimmer's direction (the subjects swam in the second lane, at a distance of 7–8 m from the camera). The camera was positioned in such a way to record the passage of the swimmer between the 10th and 20th meter from the start. After the experiments the data were downloaded to a PC and digitized using a commercial software package (Twin pro, SIMI, Germany). TI (α) was calculated as the angle between the shoulder (acromion process) and the hip (great trochanter) segment and the horizontal; this measurement was taken at the end of the insweep (when the hand is directly below the shoulder), as indicated above.

The geometric distortion introduced by the fish-eye camera was corrected by applying a fourth degree polynomial global correction technique. A calibration grid (1 m × 2 m × 1 m in the transverse, longitudinal and vertical directions, respectively) was acquired and used to estimate the distortion parameters. Ten points on the longitudinal direction and 5 points on the vertical direction (at a distance of 20 cm from each other) were marked and then used to calibrate the space. Each frame of the movie was corrected accordingly using a bilinear interpolation (Gourgolis et al. 2008). The correction was performed using the software Matlab 7 (MathWorks, Inc., USA) as indicated by Gronenschild (1997). The rotation of the camera around its optical axis, due to the anchorage system, was taken into account. The angle between the swimming pool lane and the horizontal axis of the image was estimated and used to correct the two coordinates of each digitized point on the image.

Trunk incline and frontal area

Trunk incline (α) and projected frontal area (A_{eff}) were calculated as described for subjects of Group A.

Active drag

In this group of subjects active drag was calculated as indicated in the Introduction (Eq. 5). Further details on these calculations are given in the "Discussion".

Statistics

Average values are reported ±1 SD. Significant correlation between variables in linear regressions was evaluated as indicated by Geigy Scientific Tables.

Differences between values collected on male and female swimmers (Group B) during passive measurements were evaluated by means of an unpaired Student's *t* test.

To compare data of male and female swimmers (Group B) collected during passive towing and active swimming, a two way ANOVA for repeated measures (3 speeds and 2 conditions: active and passive) was employed (SPSS, USA); the variables tested were TI and *D*. The selected speeds were 1.03, 1.20 and 1.40 for male swimmers and 1.03, 1.16 and

1.44 m s^{-1} for female swimmers. When significant *F* values were obtained, a Bonferroni test was applied post hoc to determine where the differences occurred. The Normality distribution was assessed by means of a Shapiro–Wilk Normality test (XLSTAT, Addinsoft, USA). The level of significance was set at $P \leq 0.05$.

Results

Subjects of group A: active drag measurements

The average values (±1 SD) of D_a, D_a/v^2, TI, A_{eff} and C_d as calculated/measured on subjects of group A are reported in Table 2. The relationship between active drag and speed, assessed in this group of subjects is well interpolated by the following function: $D_a = 43.7 \times v^{1.60}$, $R^2 = 0.825$, $n = 60$. The ratio D_a/v^2 is reported in Fig. 1 as a function of speed (values are means, bars represent SD). Data are well interpolated by the following function: $D_a/v^2 = 67.7 - 22.2 \times v$, $R = 0.447$, $n = 60$, $P < 0.001$. The decrease of D_a/v^2 with increasing speed suggests that, in this experimental condition, the body tends to assume a more streamlined position in water at the highest swimming speeds.

Indeed, TI decreases steadily as a function of speed ($TI = 28.9 - 13.7\ v$, $R = 0.642$, $n = 60$, $P < 0.001$): at 1.4 m s^{-1} TI is about half the value measured at 0.6 m s^{-1} (it amounts to 21 and 10° at 0.6 and 1.4 m s^{-1}, respectively). The relationship between speed and projected frontal area (Fig. 2) mirrors this trend: $A_{eff} = 0.52 - 0.21\ v$, $R = 0.591$, $n = 60$, $P < 0.001$; at 1.4 m s^{-1} A_{eff} is about half the value measured at 0.6 m s^{-1} (it amounts to 0.40 and 0.23 m^2 at 0.6 and 1.4 m s^{-1}, respectively).

On the basis of the values of D_a, v, A_{eff} and assuming a constant value for ρ (997 kg m^{-3} at 25°C) it is possible to calculate C_d. As shown by Table 2, C_d amounts, on the average, to 0.30 ± 0.09 (for all subjects at all speeds) and does not change as a function of the speed ($C_d = 0.82 + 0.39 \times v$, $R = 0.160$, $n = 60$, $P > 0.1$): it therefore does not contribute significantly to the variability of D/v^2, at least in the range of the investigated speeds.

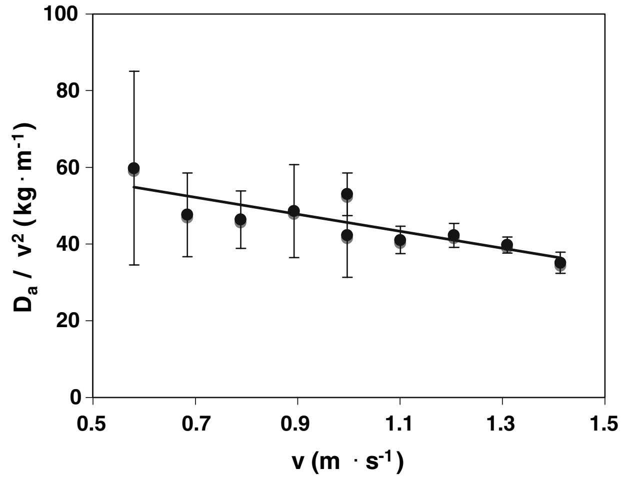

Fig. 1 Speed specific active drag (D_a/v^2) as a function of the speed in subjects of group A. Values are means, *bars* represent 1 SD. The relationship between these two parameters is well described by: $D_a/v^2 = 67.7 - 22.2 \cdot v$, $R = 0.447$, $n = 60$, $P < 0.001$

Subjects of group B: passive drag measurements

The average values (±1 SD) of D_p, D_p/v^2, TI, A_{eff} and C_d as calculated/measured on subjects of group B during the passive towing experiments are reported in Table 3. No significant differences (Student's *t* test) either in TI, A_{eff} and C_d were found between male and female swimmers at any given speed whereas D_p and D_p/v^2 were systematically lower in females (see Table 3). The relationship between passive drag and speed, assessed in this group of

Table 2 Data collected/calculated on subjects of group A when swimming by kicking the legs only (L) or when swimming the front crawl (AL)

	v (m s^{-1})	D_a (N)	D_a/v^2 (N m^{-2} s^2)	TI (degrees)	A_{eff} (m^2)	C_d
L (*N* = 6)	0.6	20 ± 8	60 ± 25	21 ± 3	0.40 ± 0.06	0.30 ± 0.11
	0.7	22 ± 5	48 ± 11	20 ± 7	0.38 ± 0.11	0.28 ± 0.13
	0.8	29 ± 5	46 ± 7	18 ± 3	0.36 ± 0.05	0.26 ± 0.04
	0.9	39 ± 10	49 ± 12	17 ± 4	0.33 ± 0.07	0.31 ± 0.12
	1.0	42 ± 11	42 ± 11	16 ± 5	0.32 ± 0.09	0.28 ± 0.10
AL (*N* = 6)	1.0	53 ± 6	53 ± 6	15 ± 3	0.31 ± 0.06	0.35 ± 0.08
	1.1	50 ± 4	41 ± 4	14 ± 3	0.30 ± 0.06	0.29 ± 0.08
	1.2	61 ± 5	42 ± 3	13 ± 3	0.28 ± 0.06	0.31 ± 0.09
	1.3	68 ± 4	40 ± 2	11 ± 2	0.24 ± 0.03	0.33 ± 0.04
	1.4	70 ± 6	35 ± 3	10 ± 2	0.23 ± 0.04	0.32 ± 0.07

Values are mean ± 1 SD

v swimming speed, D_a active drag, D_a/v^2 speed specific drag, *TI* trunk incline, A_{eff} projected frontal area, C_d drag coefficient

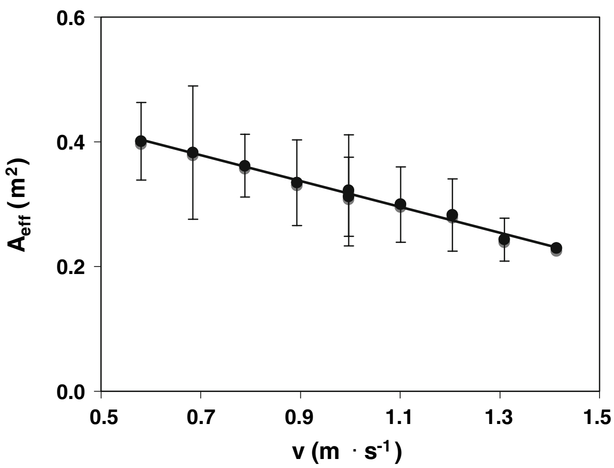

Fig. 2 Effective frontal area (A_{eff}) as a function of the speed in subjects of group A. Values are means, *bars* represent 1 SD. The relationship between these two parameters is well described by: $A_{eff} = 0.52 - 0.21\ v$, $R = 0.591$, $n = 60$, $P < 0.001$

subjects is well interpolated by the following functions: $D_p = 23.63 \times v^{1.99}$, $R^2 = 0.995$, $n = 84$ in male swimmers; $D_p = 19.11 \times v^{2.17}$, $R^2 = 0.958$, $n = 66$ in female swimmers.

As reported in Fig. 3 (values are means, bars represent SD; full circles: males; open circles: females) the D_p/v^2 ratio does not change with speed in male subjects ($D_p/v^2 = 24.5–0.61 \times v$, $R = 0.072$, $n = 84$, $P > 0.1$) whereas it increases with speed in females: $D_p/v^2 = 16.0 + 3.08 \times v$, $R = 0.391$, $n = 66$, $P < 0.01$). This suggests that female swimmers, when passively towed, tend to assume a less streamlined position in water at the highest swimming speeds whereas there is no change in "configuration" for male swimmers in the selected speed range.

Subjects of group B: swimming trials

The average values (±1 SD) of TI, A_{eff}, D_a/v^2 and D_a as calculated/measured on subjects of group B during the swimming trials are reported in Table 4. The speed, in this set of experiments was not controlled but self selected. To compare data of male and female swimmers the statistical analysis was performed on data collected at 1.03, 1.20 and 1.40 in male swimmers and at 1.03, 1.16 and 1.44 m s^{-1} in female swimmers.

The values of TI are reported in Fig. 4 as a function of the speed during the passive drag measurements (continuous lines) and during free swimming (dotted lines) in male (full circles) swimmers. This figure shows that: (1) when the subjects are passively towed their TI attains at "steady state value" (about 3.9° in male and 5.4° in female swimmers) at speeds from 1.2 to 1.8 m s^{-1}; and (2) during swimming TI is about twice the value measured during passive towing: at speeds from 1.0 to 1.6 m s^{-1} is of about 10.5° in males and 11.5° in females.

The statistical analysis performed by means of ANOVA indicated a significant difference in TI between the towing experiments and the swimming trials ($F_{1,23} = 70.08$, $P < 0.001$), whereas TI did not change as a function of speed ($F_{2,46} = 2.89$, $P > 0.05$) or gender ($F_{2,46} = 2.61$, $P > 0.05$).

Data of active drag in these subjects were calculated according to Eq. 5. The relationship between D_a and v is well described by: $D_a = 43.2 \times v^{1.72}$, $R^2 = 0.488$, $n = 55$ in male swimmers; and: $D_a = 34.1 \times v^{1.56}$, $R^2 = 0.422$, $n = 44$, in female swimmers.

The statistical analysis performed by means of ANOVA indicated that there was a significant difference between male and female swimmers ($F_{1,23} = 6.01$, $P < 0.05$); that hydrodynamic resistance changed as a function of the speed ($F_{2,46} = 124.01$, $P < 0.001$); that active drag was larger than passive drag ($F_{1,23} = 49.07$, $P < 0.001$); and that there was a significant interaction between passive and active drag at the three investigated speeds ($F_{2,46} = 11.21$, $P < 0.001$).

Moreover, the calculated D_a values for male subjects are comparable to those attained during active drag measurements in swimmers of the same sex, age and body built (male subjects of Group A).

Discussion

The principal aim of this study was to investigate the role of TI and projected frontal area (A_{eff}) in determining drag during active/passive measurements. The importance of maintaining a streamlined body position during swimming is indeed widely recognized as a key issue for improving performance. Strangely enough there are no studies in the literature (to our knowledge) that deal specifically with this topic.

According to Vogel (1994) "streamlining alone, in the absence of flexibility, gives a negative D/v^2 versus v relationship". Data of active drag reported in this paper indicate that the human body indeed changes "configuration" in water: it has a relatively lower speed specific drag (D/v^2) at high swimming speeds. The "streamlining effect" is confirmed by the observation that TI, and hence projected frontal area (A_{eff}) decreases as a function of speed during free swimming. On the other hand, the calculated values of C_d show that this parameter does not change significantly as a function of the speed. These findings therefore support the hypothesis that the variability of the D/v^2 ratio (at least at these swimming speeds) is essentially attributable to the variability of the body position in water. On this line of reasoning it seems therefore possible to

Table 3 Data collected/calculated on subjects of group B when passively towed

	v (m s^{-1})	D_p (N)	D_p/v^2 (N m^{-2} s^2)	TI (degrees)	A_{eff} (m^2)	C_d
M ($N = 14$)	0.78	14 ± 2	23 ± 4	8.9 ± 2.6	0.21 ± 0.04	0.23 ± 0.07
	1.00	25 ± 4	25 ± 4	6.3 ± 3.8	0.17 ± 0.06	0.33 ± 0.16
	1.22	36 ± 4	25 ± 3	3.8 ± 3.1	0.13 ± 0.05	0.43 ± 0.19
	1.42	47 ± 4	23 ± 2	4.9 ± 3.5	0.15 ± 0.06	0.36 ± 0.15
	1.62	60 ± 5	23 ± 2	3.6 ± 2.8	0.13 ± 0.05	0.39 ± 0.12
	1.80	77 ± 4	24 ± 1	4.3 ± 3.4	0.14 ± 0.06	0.38 ± 0.12
F ($N = 11$)	0.78	11 ± 1*	19 ± 1*	8.0 ± 3.4	0.18 ± 0.06	0.23 ± 0.06
	1.00	19 ± 3*	19 ± 3*	6.4 ± 3.6	0.16 ± 0.06	0.26 ± 0.09
	1.22	28 ± 4§	19 ± 3*	5.9 ± 3.7	0.15 ± 0.06	0.30 ± 0.15
	1.42	40 ± 5*	20 ± 3*	5.1 ± 4.1	0.14 ± 0.07	0.33 ± 0.10
	1.62	54 ± 6*	20 ± 2*	4.8 ± 4.4	0.14 ± 0.07	0.40 ± 0.28
	1.80	73 ± 7§	22 ± 2§	5.8 ± 4.9	0.15 ± 0.08	0.39 ± 0.22

Values are means ± 1 SD

v swimming speed, D_p passive drag, D_p/v^2 sped specific drag, *TI* trunk incline, A_{eff} projected frontal area, C_d drag coefficient. Statistical differences between male and female swimmers (Student's *t* test) at paired speeds * $P < 0.05$; § $0.1 < P > 0.05$

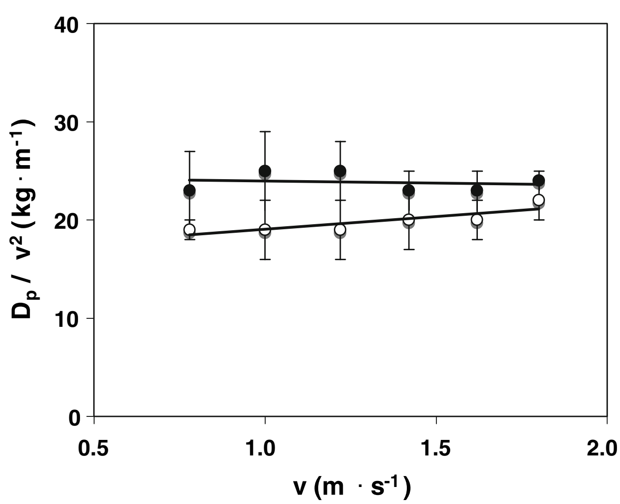

Fig. 3 Speed specific passive drag (D_p/v^2) as a function of the speed in subjects of group B. Values are means, *bars* represent 1 SD. The relationship between these two parameters is well described in female subjects by: D_p/v^2 (*open circles*) = 16.0 + 3.08 × v, $R = 0.391$, $n = 66$, $P < 0.01$). On the contrary, D_p/v^2 is independent on the speed in male subjects: D_p/v^2 (*closed circles*) = 24.5 – 0.61 × v, $R = 0.072$, $n = 84$; $P > 0.1$

tentatively estimate the values of active drag of a swimmer from values of passive drag, by knowing the difference in projected frontal area in the two conditions. However, the accuracy of such estimate can be hampered by several factors, which will be discussed further on.

It is also interesting to point out that during passive towing there is no "streamlining effect" (at least in the male subjects) since the TI is almost constant as a function of the speed (moreover, it is about half the value measured at the same speed during free swimming). Hence during passive and active drag measurements the body assumes different positions in water and this should have an effect on hydrodynamic resistance.

Critique of the methods

Leg kick and arm stroke

The data reported in this study for subjects of group A were collected when these subjects were swimming by kicking the legs only (from 0.6 to 1 m s^{-1}) or the front crawl (from 1 to 1.4 m s^{-1}). Even if these can be considered two different "modes of locomotion in water" we think that this approach could be appropriate in the context of our study. That this is indeed the case seems supported by inspection of Figs. 1 (D_a/v^2 vs. v) and 2 (A_{eff} vs. v) that show no discontinuities in the data as a function of the speed. Thus it seems appropriate to consider together leg kicking and front crawl for evaluating a broader range of body assets in water as a function of the speed.

Passive and active drag

The values of D_p reported in this study are consistent with data reported in the literature for subjects of comparable age, sex and anthropometric characteristics (e.g. $D = 29 \times v^2$ in 21 years old male swimmers, as reported by Kjendlie and Stallman 2008). Indeed, passive drag measurements show a remarkable consistency even in different experimental designs (for a review see Havriluk 2005, 2007).

On the other hand, the values of D_a calculated/measured in this study are higher than those reported by others (e.g.

Table 4 Data collected/calculated on subjects of group B during the swimming trials

	v (m s^{-1})	TI (degrees)	A_{eff} a (m^2)	D_a/v^2 (N m$^{-2\cdot}$ s^2)	D_a (N)
M ($N = 14$)	1.03 ± 0.19	10 ± 3	0.23 ± 0.05	43 ± 15	46 ± 19
	1.20 ± 0.14	10 ± 4	0.23 ± 0.07	42 ± 17	60 ± 23
	1.40 ± 0.14	11 ± 3	0.24 ± 0.05	46 ± 19	86 ± 31
	1.62 ± 0.14	11 ± 3	0.24 ± 0.05	46 ± 20	119 ± 52
F ($N = 11$)	1.03 ± 0.11	11 ± 3	0.23 ± 0.06	33 ± 8	35 ± 8
	1.16 ± 0.14	12 ± 2	0.24 ± 0.03	36 ± 10	48 ± 11
	1.28 ± 0.16	12 ± 2	0.24 ± 0.04	36 ± 11	57 ± 15
	1.44 ± 0.18	11 ± 2	0.23 ± 0.04	35 ± 9	72 ± 22

Values are mean ± 1 SD

v swimming speed, *TI* trunk incline, A_{eff} projected frontal area, D_a/v^2 speed specific drag, D_a active drag

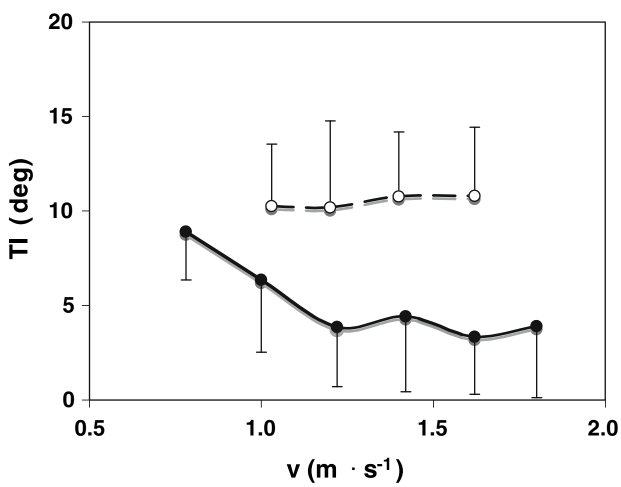

Fig. 4 Trunk incline (*TI*) as a function of the speed in male subjects of group B (*open circles* while passively towed; *closed circles* while swimming the front crawl). Values are means, *bars* represent 1 SD. Data referring to female swimmers are reported in Tables 3 and 4

$D = 33 \times v^2$ in 21 years old male swimmers, as reported by Kjendlie and Stallman 2008; $D = 26 \times v^{2.12}$ in experienced male swimmers, as reported by Toussaint et al. 1988).

As pointed out by Havriluk (2007), this disparity could be due either to the fact that in these methods different variables were measured or to the fact that there is a measurement error. As shown in his paper, the comparison of passive and active drag methodologies revealed that the active drag methods based on the "equal power assumption" (e.g. Kolmogorov and Duplisheva 1992) and on the MAD system (e.g. Toussaint et al. 1988) yield drag coefficients of similar magnitude to that of passive methods whereas the method proposed by di Prampero et al. (1974), and utilized in this study for determining active drag in subject's of group A, measures a different C_d.

In the meta-analysis proposed by Havriluk (2007), C_d was calculated on the basis of the $D = kv^2$ equation (as experimentally determined in 36 different studies) assuming a reference area calculated from the individual values of BM and stature. As calculated (i.e. assuming a constant reference area), C_d should obviously depend on the body position in water. Indeed, quite large differences in C_d during passive towing are found depending on the body position (e.g. head above or below the water surface; prone or dorsal streamline…).

As pointed out by Havriluk (2007) is "unlikely that a swimmer could be as streamlined during actual swimming motions as during passive streamlining". Thus, a similar C_d between passive and active drag measurements have to be attributed to a similar position of the swimmer in the two conditions. The data reported in our study indicated that this could indeed be the case since: (1) in the MAD system method the legs are supported by a pull buoy thus maintaining the swimmer horizontal (and streamlined); (2) the perturbation method can be applied only at maximal speeds where the body angle with the horizontal is the least.

The data of active drag calculated in this study are, on the other hand, comparable to those assessed with the method proposed di Prampero et al. (1974). It must be pointed out that this method is based on an indirect extrapolation technique and could be utilized only to assess active drag at aerobic speeds (up to about 1.4 m s^{-1}); it is therefore fair to say that it has its own limitations. However, it seems to offer a more "ecological" approach to swimming since, in comparison with the MAD system it does not affect (or to a minor degree) the body position in water and in comparison with the perturbation method it could be applied to investigate drag at different (sub-maximal) speeds.

C_d and projected frontal area

The values of C_d calculated in this study (on the average 0.37 and 0.31 in male and in female swimmers of group B and 0.30 in subjects of group A) are comparable with those calculated by Zaidi et al. (2008) by means of 2D computational fluid dynamics (0.27–0.37, with different positions of the head). Moreover, in accordance with these authors, we found that the drag coefficient was almost constant on the studied speed range.

On the other hand, our values are in the lower range of those reported by others (the frequency distribution of which peaks at about 0.7, as reviewed by Havriluk 2007). The drag coefficient is generally calculated based on values of drag and of a "reference area". Coefficients based on total surface area (or wetted area) are generally utilized for streamlined objects and coefficients based on cross sectional area (or frontal area) are generally utilized for simple shapes (such as cylinders). The choice of the reference area has a crucial effect in determining the absolute value of C_d: differences up to an order of magnitude can be found, as an example, in fish studies (Alexander 1990). As pointed out by Havriluk (2005) in his meta analysis of passive drag forces, the reference area is generally assumed to be constant for "an inactive swimmer" but any area utilized can vary during testing according with the fluctuations in the water lever around the body (wetted area) and according to the swimmer's ability to maintain a streamlined position (cross sectional area). There is therefore a "potential source of error" in using estimated values that do not take into account this source of variability.

In other words, the constant k, in the $D = kv^n$ relationship, could not be considered an index of C_d in swimming if the reference area of choice does not take into account the body incline.

The formula to calculate the "reference area" proposed in this study attempts to take into account TI (the term α), frontal area (the term A_f) and wetted area (the term $BSA/2$) of the swimmer. The values of A_{eff} reported in this study (on the average 0.15 and 0.33 m^2 in subjects of group B and A, respectively) are significantly lower than those reported in studies of passive towing (e.g. 0.65–0.75 m^2 as reported by Havriluk 2005), simply because they take into account the effect of changes of TI with increasing speed.

Regardless of the absolute values of A_{eff} (and hence of C_d), the same method to calculate the reference area was utilized in the two conditions (of passive towing and "free swimming"). This makes us confident that the calculations of D_a were not affected by the method utilized to calculate the reference area since they depend, essentially, on the observed differences in body angle between the two conditions.

The calculation of D_a

Passive drag measurements were carried out at speeds different from (but in the same range of) those attained during the swimming trials. Since A_{eff} during passive towing was found to be pretty constant, at least at speeds from 1.2 to 1.8 m s^{-1}, to calculate active drag we have utilized as "passive A_{eff} values" the average A_{eff} value calculated in this speed range for each subject. The values of D_p/v^2 utilized in the same equation were obtained from the D_p versus v relationship assessed in each subject during passive towing. The A_{eff} values during the swimming trials were calculated for each subject and speed; active drag was finally calculated by multiplying the so obtained D_a/v^2 ratio for the speeds attained by each subject during the swimming trials.

Active drag turned out to be larger than passive drag both in male and female swimmers as expected on theoretical grounds and as found for the D_p versus v relationship. Moreover, the calculated D_a values for male subjects ($D_a = 43.16 \times v^{1.72}$, $R^2 = 0.488$, $n = 55$) turned out to be of the same order of magnitude of those attained during active drag measurements in swimmers of the same sex, age and body built (group A: $D_a = 43.71 \times v^{1.60}$, $R^2 = 0.825$, $n = 60$).

The lower coefficient of determination ($R^2 = 0.4$–0.5) of the relationships between estimated drag values and speed in comparison with those obtained by using the passive and active drag values ($R^2 = 0.8$–0.9) underlines the large variability of the calculated D_a values both in male and female swimmers. A possible source of this variability could be attributed to the variability of TI. This parameter is indeed dependent on the stroke cycle and can be better assessed with a 3D kinematic analysis of the entire stroke. Moreover, both wetted area and cross sectional area are expected to change during the stroke cycle, affecting A_{eff} in a manner difficult to predict/determine.

Another factor that has to be taken into account when data of active drag are estimated from data of passive drag is related to the inter-subject's difference in skill level, such as the more or less effective use of the leg kick in maintaining the body horizontal or the capability to minimize lateral displacement or body roll (which indeed could affect D_a but not D_p).

Even if subjects of group B are not directly comparable to subjects of group A in terms of skill (see performance times in Table 1) D_a was found to be similar in the two groups suggesting that either this factor has a lower importance than TI in determining hydrodynamic resistance or that TI itself takes into account for these differences.

Another reason why this method should be utilized with some caution is that it is based on the assumption that pressure drag accounts for the majority of total hydrodynamic resistance ($D_{pr} \approx D$). However, as outlined in the Introduction, the D_{pr} contribution to D is speed dependent (the larger the speed, the smaller its contribution); the reliability of these calculations, therefore, is also dependent on the velocity used. Our results indicate that this method could be "safely" applied to estimate drag up to speeds of 1.4 m s^{-1} (at which D_{pr} is about 63% of D); this could not be the case at higher speeds where the contribution of D_{pr} is reduced.

The differences in trunk incline during active and passive drag measurements

The most interesting finding of this study was that TI is larger during active than passive drag, for any given speed and subject. Why this is the case could be tentatively explained by the findings of Yanai (2001) who suggested that the hydrodynamic forces acting on the hand generate a counter clockwise torque about the centre of mass of the subject leading "the legs to sink". As proposed by this author, the buoyant torque and the leg kick function to counteract this torque in the attempt to maintain a horizontal alignment during front crawl swimming.

The data reported in this paper suggest that this "counter action" is not completely effective, at least in the range of speed we utilized, when compared to the position the body assumes when passively towed. A better understanding of the reasons why there is this difference in TI in the two conditions could be possibly obtained by means of 3D computational fluid dynamics.

Conclusions

Data reported in this study indicate that: (1) the human body changes "configuration" with increasing speed: indeed speed specific drag (D/v^2) decreases as the speed increases; (2) this change is associated with a change in the projected frontal area of the swimmer: indeed A_{eff} (along with TI) decreases with increasing speed; whereas (3) no changes in the drag coefficient (C_d) are observed as a function of the speed. Therefore, the changes in D/v^2 are related to changes in TI (and hence in A_{eff}) but not in C_d.

Data reported in this study also indicate that projected frontal area (along with TI) is lower during passive drag measurements than while swimming, thus suggesting that active drag should be larger than passive drag. Moreover, when active drag is estimated based on data of passive drag (measured while the swimmers are towed at constant velocity at the surface) and projected frontal area, the values turn out to be close to those of active drag reported in the literature for subjects of comparable age, sex and body built.

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