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Research article

Estimating Active Drag Based on Full and Semi-Tethered Swimming Tests

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Abstract

During full tethered swimming no hydrodynamic resistance is generated (since v = 0) and all the swimmer's propulsive force (F_P) is utilized to exert force on the tether ($F_T = F_P$). During semi-tethered swimming F_P can be made useful to one of two ends: exerting force on the tether (F_{ST}) or overcoming drag in the water (active drag: *Da*). At constant stroke rate, the mean propulsive force (F_P) is constant and the quantity F_P - F_{ST} (the "residual thrust") corresponds to *Da*. In this study we explored the possibility to estimate *Da* based on this method ("residual thrust method") and we compared these values with passive drag values (*Dp*) and with values of active drag estimated by means of the "planimetric method". Based on data obtained from resisted swimming (full and semi-tethered tests at 100% and 35, 50, 60, 75, 85% of the individual F_T), active drag was calculated as: $Da_{ST} = ka_{ST} \cdot v_{ST}^2 = F_P - F_{ST}$ ("residual thrust method"). Passive drag (*Dp*) was calculated based on data obtained from passive towing tests and active drag ("planimetric method") was estimated as: $Da_{PL} = Dp \cdot 1.5$. Speed-specific drag ($k = D/v^2$) in passive conditions (*kp*) was ≈25 kg·m^{-1} and in active conditions (*ka*) ≈38 kg·m^{-1} (with either method); thus, $Da_{ST} > Dp$ and $Da_{ST} \approx Da_{PL}$. In human swimming active drag is, thus, about 1.5 times larger than passive drag. These experiments can be conducted in an ecological setting (in the swimming pool) by using basic instrumentation and a simple set of calculations.

Key words: Hydrodynamic resistance; resisted swimming; front crawl; biomechanics; water locomotion.

Introduction

From Newton's third law, during (free) swimming at constant speed the sum of the propulsive (F_P) and resistive (F_D, hydrodynamic resistance) forces must be zero; F_P and F_D must, thus, be in balance:

$$F_P + F_D = 0$$
$$F_P = - F_D$$

To note, F_P (or F_D) is only a fraction of the total force (F_{TOT}) a swimmer can generate in water and propelling efficiency indicates this fraction ($\eta_p = F_P / F_{TOT}$ or F_D / F_{TOT}) (Zamparo et al., 2020). In addition, it is important to note that F_D refers to active drag (*Da*): e.g. the resistive forces experienced during swimming. Whereas, during passive drag (*Dp*) experiments no propulsion is provided by the swimmer, during swimming the limb movements create propulsion but also create additional resistance; thus, *Da* is expected to be significantly larger than *Dp*. How to measure *Da* is still a controversial issue in swimming literature (Formosa et al., 2012; Havriluk, 2007; Sacilotto et al., 2023; Toussaint et al., 2004; Zamparo et al., 2020) but the most recent methods developed to evaluate drag indicate that *Da* is about 1.5-2.0 times larger than *Dp* (Gatta et al., 2016; Narita et al., 2017).

In this study, we explored the possibility of estimating active drag based on full tethered and semi-tethered swimming tests, by using a simplified version of the "residual thrust method" (Narita et al., 2017; Shimonagata et al., 1999; Takagi et al, 1999). As schematically represented in Figure 1 (central panel), during full tethered swimming no hydrodynamic resistance is generated (F_D = 0 since v = 0) and all the swimmer's propulsive force is utilized to exert force on the tether ($F_P = F_T$). Instead, during semi-tethered swimming (panel on the right in Figure 1) propulsive force can be made useful to one of two ends: exerting force on the tether (F_{ST}) or (actively) overcoming drag in the water ($-F_D$), thus:

$$F_P = F_{ST} + (-F_D) \text{ or}$$
$$F_T = F_{ST} + (-F_D) \text{ hence}$$
$$(F_T - F_{ST}) = -F_D$$

In the (few) studies aiming to calculate active drag based on this method (Narita et al., 2017; Shimonagata et al., 1999; Takagi et al, 1999) it was observed that the difference between F_T and F_{ST} (e.g. F_D) is larger than the values of passive drag (assessed by towing the swimmers in their best hydrodynamic position); this difference was termed "active drag" by Shimonagata et al. (1999) and attributed to the additional resistance that is created by the swimmer's movements during the stroke. Takagi et al. (1999) defined "kinetic drag" (*Dk*) as the difference between passive drag (*Dp*) and active drag; according to these authors, while *Dp* mainly depends on friction and pressure drag, *Dk* consists mainly of wave-making drag that originates from the stroking movements of arms and legs. In the studies of Takagi et al. (1999) and Narita et al. (2017), the difference between F_T and F_D is called "residual thrust"; this term derives from shipbuilding engineering where data from different tests (e.g. open water test, resistance test, self-propulsion test) on tank basins are integrated to predict speed and power output in ship models (Molland, 2011). Whereas the experimental protocol utilized by Takagi et al. (1999) and Narita et al. (2017) requires specific instrumentation and an elaborate/time-consuming data analysis, that proposed by Shimonagata et al. (1999) can be conducted in the pool, requires only basic instrumentation and a simple set of calculations.

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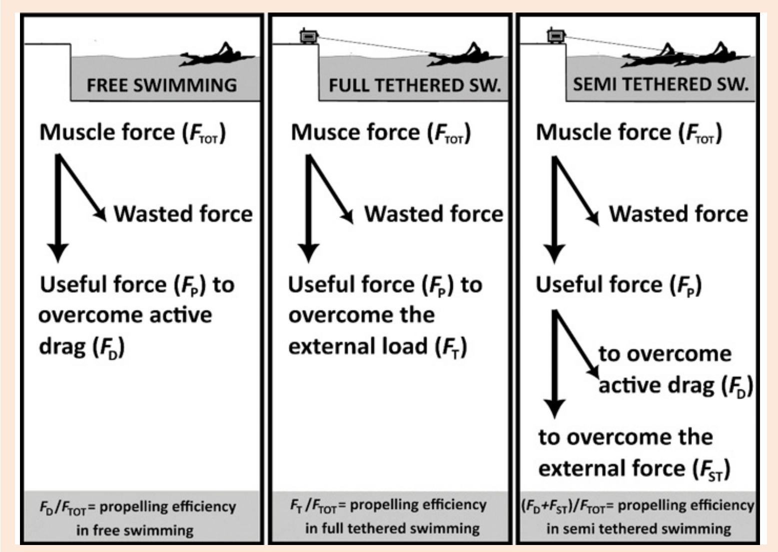

Figure 1. Schematic representation of the forces at play in different conditions. Panel on the left: free swimming; central panel: full tethered swimming; panel on the right: semi-tethered swimming. In all cases, a fraction of the force generated by the muscles (F_{TOT}) is wasted to give water kinetic energy (e.g. is not useful for propulsion). The fraction of useful force (F_P) to total force is termed propelling efficiency (F_P / F_{TOT}) and is assumed to be the same in all conditions. The useful force is then used to overcome drag in free swimming (F_D) and/or the external load in full tethered swimming (F_T) and semi-tethered swimming (F_{ST}).

In the present study we explored the possibility to estimate active drag with an experimental protocol similar to that proposed by Shimonagata et al. (1999) and we estimated active drag also by means of the method proposed by Gatta et al. (2015) ("planimetric method"); in this case active drag can be calculated/estimated based on values of passive drag by knowing that speed-specific drag in active conditions (*ka*) is about 1.5 times larger than in passive conditions (*kp*) (and by assuming that $F_D = k\ v^2$). According to this method, the difference between *ka* and *kp* stems from differences in frontal area (*A*, as in $k = ½ A\ Cd\ \rho$) since additional resistance is created by the swimmer's movements during the stroke (e.g. the average *A* is larger in active than in passive conditions). The difference between *ka* and *kp* is, thus, conceptually analogous to the "kinetic drag" as calculated by means of the "residual thrust method".

In summary, the research question of this study was to verify whether these two approaches ("planimetric method" and "residual thrust method") lead to similar results (e.g. measure the same quantity). We expected values of active drag assessed by means of the "residual thrust method" to be larger than those of passive drag but comparable to those calculated by means of the "planimetric method".

Methods

Experimental design

This is an observational research study. Full or semi-tethered tests and passive towing tests were carried out with the aim of determining passive drag (*Dp*) and active drag (*Da*) by using two different methods ("planimetric method" and "residual thrust method") which are described in detail below. All swimmers were familiarized with testing procedures during several training sessions; a 1000-m warm-up session at low-to-moderate intensity preceded the testing sessions; tests were conducted for one swimmer at a time and the order in which tests were performed was randomized across swimmers.

Subjects

Fourteen male sprinters (age: 23.1 ± 2.0 years, stature: 1.89 ± 0.05 m, body mass 83.6 ± 7.2 kg) specialized in 50- and 100-m front crawl were recruited for the study. All swimmers were involved in their national team in the year before the test (performance level: 93 ± 2 % of the world record in 50-m front-crawl and 810.7 ± 69.4 Fina Points). Subjects were informed of the study procedure and provided written informed consent before their inclusion in this study. The project was approved by the local Bioethics Committee (Approval code: 0196686) and conducted in accordance with the principles of the Declaration of Helsinki.

Procedures

Passive drag measurements and "planimetric method"

Passive drag (D_P) was measured during five 25-m passive towing trials at a constant velocity (v_{TOW}) of 1.0, 1.3, 1.6, 1.9 and 2.2 $m \cdot s^{-1}$; 3-min pauses separated the trials. Passive drag values (D_P) were determined by means of an electromechanical device composed of a low-voltage isokinetic engine (Swim-Spektro, Talamonti Spa, Ascoli Piceno, Italy) and set equal to the forces exerted by the device when towing the swimmer at the predetermined velocities. The average force between the 10th and 20th m from the starting wall was calculated and used in the following analysis; see Scurati et al. (2019) for further details. Details on calibration procedures are reported in the Supplementary Materials.

For each swimmer, the relationship between D_P and v_{TOW} was fitted with a quadratic function, and speed-specific drag in passive condition (*kp*) was computed as Dp/v_{TOW}^2. Active drag was estimated from passive drag values, by using the "planimetric method": Da_{PL} at a given speed was calculated as $kp \cdot 1.5 \cdot v^2$ (see Gatta et al. 2015 for further details).

Tethered and semi-tethered tests and "residual thrust method"

During these tests, the swimmers wore a waist belt and were connected to a load cell and/or an electro-mechanical device through a non-elastic (steel) cable. Neither push-off from the starting wall nor breathing were allowed during these tests and the stroke rate was not controlled; the only instruction the swimmers were given was to swim at maximum effort in all trials.

The full tethered trial was a 15-s all-out test, and the instantaneous values of full tethered force (F_T) were measured using a load cell (Globus™, Codognè, Italy); the average value of F_T (in the 15 s time interval) was used in further analysis (see Gatta et al. 2015 for further details). During the semi-tethered tests, the participants were asked to swim at maximal intensity while pulling imposed loads of 66, 90, 115, 135, 160, 187 N (about 35, 50, 60, 75, 85% of the individual F_T); these tests were separated by a minimum of 3 min of active recovery. The Swim-Spektro device was used to control the external load and to measure the corresponding swimming velocity (v_{ST}). The swimmers were asked to complete 10 stroke cycles (about 10 s) and the average speed and arm stroke frequency (*SF*) were calculated and used for the following analysis. The participants were also asked to swim at maximal intensity without any added load (0% of individual F_T); in this condition the swimmers reached their maximal free-swimming velocity (v_{MAX}).

Active drag ("residual thrust method") was calculated based on full tethered and semi-tethered data by using two (complementary) approaches:

1- By assuming $F_P = F_T$, active drag can be simply calculated as: $Da_{ST} = F_T - F_{ST}$. For each swimmer, the relationship between Da_{ST} and v_{ST} was fitted with a quadratic function and the active drag coefficient (e.g. speed specific drag, ka_{ST}) was computed as Da_{ST}/v_{ST}^2.

2- Active drag coefficient (ka_{STfit}) was also estimated (for each swimmer) by fitting data of the semi-tethered tests with the following equation: $F_{ST} = F_P - ka_{STfit} \cdot v_{ST}^2$. Input data in the model were F_{ST} and v_{ST}, whereas output data were F_P (the mean propulsive force) and ka_{STfit}. In addition, *i)* the estimated values of speed at $F_{ST} = 0$ were calculated as $\sqrt{F_P/ka_{STfit}}$, *ii)* the estimated values of force (F_P) at $v = 0$ were compared with the measured values of F_T, and *iii)* the estimated values of speed (at $F_{ST} = 0\%$) were compared with the measured values of v_{MAX}. The typical behavior (in a representative swimmer) of the model curves ($F_{ST} = F_P - ka_{STfit} \cdot v^2$ and $Da_{STfit} = ka_{STfit} \cdot v^2$) is reported in Figure 2.

Statistical analyses

Data are reported as mean and standard deviation. Normal distribution of drag and *SF* variables was assessed using the Shapiro-Wilk test. Preliminary statistical analyses were carried out using a repeated measures one-factor analysis of variances (ANOVA) to determine whether *SF* and ka_{ST} changed with the external load. In the case of a significant F ratio, a Bonferroni post hoc test was used to determine pairwise differences between conditions.

One-factor repeated measures ANOVA was also used to identify differences in speed-specific drag as determined with the different methods (k_P, ka_{PL}, ka_{ST} and ka_{STfit}). In addition, Bland-Altman plots were used to verify the level of agreement between ka_{ST} and ka_{PL} and between ka_{ST} and k_{STfit}.

JASP 2020 (JASP Team), SigmaPlot 11.0 (Systat software) and Inkscape 1.2.2. (Inkscape) were used for statistical tests, data analysis and graphical plots; the level of statistical significance was set at $p < 0.05$. Python (3.8.8) with the package Scipy (1.6.2) was used for model fitting.

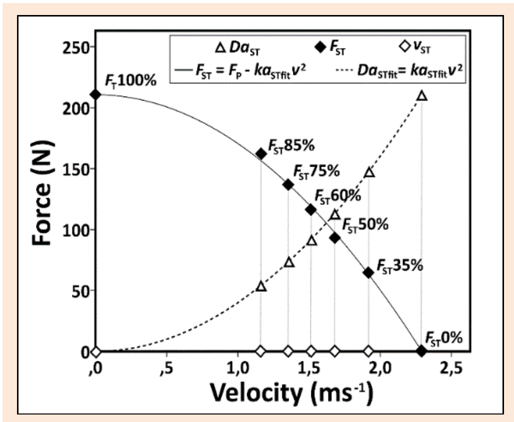

Figure 2. The relationship between the force exerted to overcome the external load (F_{ST} or F_T, filled diamonds) or the force exerted to overcome the hydrodynamic resistance (Da_{ST}, open triangles) and swimming speed (v_{ST}, open diamonds). Data refer to a representative swimmer and lines represent model's best fit.

Results

Descriptive parameters for the full and semi-tethered tests are reported in Table 1: when the external load increases (F_{ST}), swimming speed (v_{ST}) and active drag (Da_{ST}) are bound to decrease. The relative values (mean ± SD) of F_{ST}, in percentage of the individual F_T, were 35.5 ± 2.5. 48.4 ± 3.4. 61.9 ± 4.4. 72.6 ± 5.1 and 86.1 ± 6.1 %.

Table 1. Mean (± SD) data assessed during the resisted swimming tests (semi-tethered and full tethered swimming).

v (m.s^{-1})	External Load (N)	*SF* (cycles·min^{-1})	Da_{ST} (N)	ka_{ST} (kg·m^{-1})
2.22 (± 0.07) [v_{MAX}]	0.0 [F_{ST}]	59.6 (± 3.5)	186.8 (± 13.2)	37.9 (± 2.0)
1.70 (± 0.14) [v_{ST}]	66.0 [F_{ST}]	59.9 (± 3.7)	120.8 (± 13.2)	41.9 (± 5.5)
1.55 (± 0.12) [v_{ST}]	90.0 [F_{ST}]	60.2 (± 3.3)	96.8 (± 13.2)	40.3 (± 5.2)
1.36 (± 0.15) [v_{ST}]	115.0 [F_{ST}]	60.2 (± 3.6)	71.8 (± 13.2)	39.4 (± 9.1)
1.19 (± 0.18) [v_{ST}]	135.0 [F_{ST}]	60.4 (± 3.9)	51.8 (± 13.2)	37.5 (± 11.4)
1.00 (± 0.19) [v_{ST}]	160.0 [F_{ST}]	60.8 (± 4.1)	26.8 (± 13.2)	27.0 (± 14.7) *
0.00 [v_T]	186.8 (± 13.2) [F_T]	60.5 (± 3.1)	0.0	-

Active drag was calculated, at each load, as: $Da_{ST} = (F_T - F_{ST})$. Active drag coefficient was calculated as $ka_{ST} = Da_{ST} / v_{ST}^2$. *v*: swimmer's velocity; v_{MAX}: maximal free-swimming velocity; v_{ST}: swimming velocity during semi-tethered swimming; F_{ST}: the external load during semi-tethered swimming; F_T: the external load during full-tethered swimming; *SF*: stroke frequency; Da_{ST}: active drag, as determined by means of the "residual thrust method"; ka_{ST}: active drag coefficient, as determined by means of the "residual thrust method"; * significantly different from all other conditions of ka_{ST}.

Table 2. Individual values of speed specific drag as calculated based on the different methods. Data are means (± SD).

	Kp **(kg·m^{-1})**	***kaPL*** **(kg.m^{-1})**	***kaST*** **(kg·m^{-1})**	***kaST fit*** **((kg·m^{-1})**
S1	23.1 (±3.6)	34.7 (±3.6)	42.9 (±9.6)	36.6 (±2.5)
S2	25.5 (±3.4)	38.2 (±3.4)	39.6 (±1.7)	40.1 (±1.0)
S3	25.0 (±3.3)	37.5 (±3.3)	38.8 (±5.9)	39.5 (±2.5)
S4	24.9 (±3.7)	37.3 (±3.7)	39.9 (±7.3)	38.0 (±3.6)
S5	26.9 (±4.0)	40.4 (±4.0)	38.1 (±8.2)	37.8 (±5.7)
S6	24.3 (±3.0)	36.5 (±3.0)	35.0 (±11.0)	43.4 (±4.0)
S7	22.1 (±4.1)	33.2 (±4.1)	32.5 (±5.2)	41.8 (±1.5)
S8	27.4 (±3.9)	41.1 (±3.9)	35.3 (±4.6)	42.7 (±1.4)
S9	21.0 (±3.9)	31.5 (±3.9)	28.6 (±7.2)	42.4 (±1.2)
S10	28.2 (±2.4)	42.3 (±2.4)	55.8 (±10.3)	37.1 (±1.7)
S11	24.1 (±4.1)	36.2 (±4.1)	33.7 (±8.6)	41.8 (±4.6)
S12	25.4 (±3.5)	38.0 (±3.5)	30.8 (±6.5)	38.9 (±2.5)
S13	19.6 (±9.7)	29.3 (±9.7)	27.5 (±10.8)	43.9 (±1.7)
S14	26.6 (±3.7)	39.9 (±3.7)	44.1 (±5.2)	40.4 (±3.7)

kp: passive drag coefficient; ka_{PL} = active drag coefficient, as determined by means of the "planimetric method"; ka_{ST} = active drag coefficient, as determined by means of the "residual thrust method"; ka_{STfit} = active drag coefficient, as determined by means of the "residual thrust method" (model fitting).

Speed-specific active drag values (ka_{ST}) were rather stable across load conditions but for the highest load (160 N) were ka_{ST} is sensibly reduced (Table 1). A significant difference in ka_{ST} was indeed observed at the highest F_{ST} compared to all the other loads (p always < 0.001) but no other post-hoc comparisons were significant (ANOVA main effect for ka_{ST}: $F_{5.65} = 11.680$; $p < 0.001$; $\eta^2 = 0.473$). Individual values of ka_{ST} (calculated as the average value, at all loads, for each swimmer) are reported in Table 2, average values are reported in Figure 3.

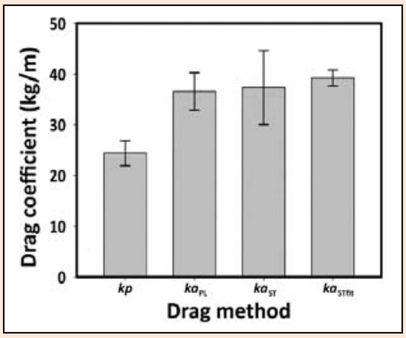

Figure 3. Mean ± SD speed specific drag, as calculated based on the different methods. *kp*: passive drag coefficient; ka_{PL} = active drag coefficient, as determined by means of the "planimetric method"; ka_{ST} = active drag coefficient, as determined by means of the "residual thrust method"; ka_{STfit} = active drag coefficient, as determined by means of the "residual thrust method" (model fitting). Individual values are reported in Table 2.

No significant differences in *SF* were observed across load conditions (ANOVA main effect for *SF*: $F_{6.78} = 1.380$; $p = 0.233$; $\eta^2 = 0.096$), comforting the assumption of constant F_P.

The fitted model parameters were always significant (p always <0.001) and the coefficient of determination (R^2) was always higher than 0.94. The fitted active drag coefficient (ka_{STfit}) was 40.3 ± 2.4 kg·m^{-1} (see Figure 3, and Table 2 for the individual values) and the fitted value of F_P was 193.0 ± 17.4 N. No differences (paired t-test) were detected between F_T (186.8 ± 13.2 N) and F_P (p = 0.194; CI: -16.061 - 3.599) and a 1.3% difference was observed between the (maximal) speed at $F_{ST} = 0$ (2.19 ± 0.08 m·s^{-1}) and v_{MAX} (2.22 ± 0.07 m·s^{-1}) (p < 0.001; CI: -0.022 - 0.042). For all the tested athletes, the measured F_T was within the 95% confidence range of the mean propulsive force (F_P).

Dp was: 30.1 ± 7.3, 42.4 ± 5.8, 60.0 ± 7.4, 85.9 ± 10.0 and 121.9 ± 11.1 N at 1.0, 1.3, 1.6, 1.9 and 2.2 m·s^{-1}, respectively. Individual *kp* data were obtained by fitting individual *Dp* data with quadratic functions (R^2 = 0.96 ± 0.06, SE error = 6.8 ± 1.4); individual *kp* and ka_{PL} values are reported in Table 2, average values in Figure 3.

A significant main effect of the drag method was observed in the one-factor ANOVA with repeated measures for drag values ($F_{3.39} = 41.601$; $p < 0.001$; $\eta^2 = 0.762$); Bonferroni post hoc test reveals *kp* significantly lower than ka_{ST} (p < 0.001; CI: -16.993 - -8.510), ka_{STfit} (p < 0.001; CI: -19.959 - -11.473) and ka_{PL} (p < 0.001; CI: -16.530 - -8.047). No differences were detected among ka_{ST}, ka_{STfit} and ka_{PL} (p always higher than 0.183) (see Figure 3).

The results of the Bland–Altman analyses are reported in the Figure 4. The comparisons between Da_{ST} and Da_{PL} and between Da_{ST} and Da_{STfit} showed consistent distributions and a low bias (-2.4 and 6.2 N, respectively) with limits of agreement ranging from -29.5 to 24.6 N and from -29.5 to 42.0, respectively.

Discussion

In this study, active drag values calculated based on full and semi-tethered swimming tests ("residual thrust method") were compared with *i)* passive drag values, as measured during passive towing trials, and *ii)* active drag values, as calculated by means of the "planimetric method". Passive drag was significantly lower than active drag (measured by any method) and no differences were detected between speed-specific active drag values (ka_{ST}, ka_{STfit} and ka_{PL}). We can thus conclude that, since these two approaches ("planimetric method" and "residual thrust method") lead to similar results, they probably measure the same quantity.

Dp values reported in this study are consistent with those reported in the literature, for a review, see (Gatta et al., 2015; Narita et al., 2017; Gatta et al., 2016). Regarding *Da*, while some studies report active drag equal or even lower than passive drag (Kolmogorov and Duplishcheva, 1992; Toussaint et al., 1988), others indicate that the former is larger than the latter (Formosa et al., 2012; Gatta et al., 2015; Hazrati et al., 2016; Narita et al., 2017; Shimonagata et al., 1999; Takagi et al., 1999). Given the large variability in the active drag estimates reported in the literature, the observation that two independent methods give comparable results constitutes a step forward in our understanding of the forces that resist motion in swimming.

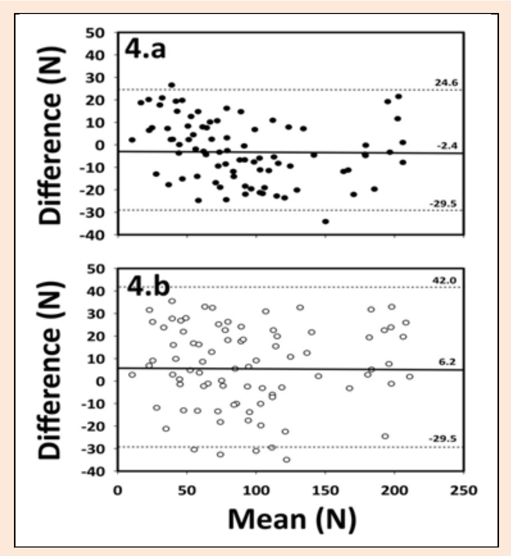

Figure 4. Bland–Altman plots for the comparison between active drag coefficient estimated using resisted swimming (Da_{ST}) and estimated using the planimetric method (Da_{PL}) (panel 4.a) or between Da_{ST} and active drag coefficient estimated using the fitted model (Da_{STfit}) (panel 4.b). The solid black line represents the mean of the differences (mean bias), and the two dotted lines represent the 95% confidence interval of limits of agreement.

Da_{ST} and Da_{STfit} data reported in this study are consistent with data obtained by others (Narita et al., 2017; Shimonagata et al., 1999; Takagi et al, 1999) that applied the "residual thrust method", although some differences in the *Da/Dp* ratio could be observed among studies (*Da/Dp* ≈1.5 in our study); this could be attributed to differences in the experimental protocol but also to differences among the participants. Indeed, as schematically represented in Figure 1, the partitioning between F_{ST} and F_D could also depend on the capability of a swimmer to minimize the latter. In general terms, inter-subject differences in F_D could be expected based on differences in the anthropometric characteristics (that influence passive drag) and in technical skill (that influences active drag). Indeed. swimmers with good technical skills have a lower active drag than less proficient ones (Pendergast et al., 2005). This suggests that the *Da/Dp* ratio can be expected to depend on the technical skills of a swimmer and to decrease with training.

Then, a swimmer able to minimize F_D could maximize the force exerted on the tether (F_{ST}) at a given external load. F_{ST} will thus depend on the muscle force the swimmers can generate (F_{TOT}), on their propelling efficiency (F_P / F_{TOT}) but also on the partitioning between F_{ST} and F_D. Thus, data reported in this study not only point out at the differences that can be expected between active and passive drag in general terms but also indicate that care should be taken when discussing data derived from semi-tethered tests (because the force balance depends also on propelling efficiency, and hence on the swimmer's technical skills).

Indeed, it was recently suggested that the capability of a swimmer to exert force during a semi-tethered trial depends (among the others) on the propulsive force necessary to overcome drag during these tests. Soncin et al. (2021) indeed observed that the correlation between semi-tethered force and swimming performance is higher when the effect of drag forces is accounted for. Unfortunately, in their paper only correlational parameters are reported (no actual data of semi-tethered force or drag force) and thus further comparisons with data reported in this study are not possible.

The main limitation of the active drag estimation based on full and semi-tethered trials is strongly inherent to the assumption of steady-state swimming conditions, but the cyclic actions of swimming create a complexity of unsteady flow mechanics that affect hydrodynamic resistance. However, currently its effects on *Da* seem impossible to measure directly (Takagi et al., 2021). Furthermore, this method does not clarify the impact of the intracyclic variation of drag because the effect of the force variation around the mean was not considered and appears difficult to evaluate due to the connection between the tether and the swimmer.

The "residual trust method" proposed in this study is based on the assumption that a swimmer can deliver an equal force during either full towing, free swimming or swimming against an external load. For this assumption to be true F_{TOT} and F_P must be the same in all conditions (see Figure 1); in other words, F_P is assumed to be constant as well as propelling efficiency (F_P/F_{TOT}). In this study, no differences were detected between (measured) F_T and the values of F_P estimated by the model and no differences in *SF* were observed across load conditions, comforting the assumption of constant F_P. In addition, F_T is close to the (active) drag force that can be calculated from the Da_{PL} *vs. v* relationship at maximal swimming speed (Da_{ST} = 0%, see Figure 2) as observed in a previous study (Gatta et al., 2016) and similar values of propelling efficiency ($F_P/F_{TOT} = 0.4$) were reported in full tethered swimming and in free swimming (Gatta et al., 2018). It is, thus, fair to assume that this state of affairs does not change in the case of semi-tethered swimming tests, thus supporting the assumption that both F_P and propelling efficiency (F_P/F_{TOT}) remain constant.

The observed lack of differences in *SF* among conditions is relevant also because, as suggested in the literature (Narita et al., 2017, Takagi et al., 1999), the assumption that a swimmer adopts the same technique, body position and kinematics in different experimental conditions is considered to be valid when the stroke rate is maintained constant. Thus, as our swimmers maintained their stroke rate, it is likely that they managed to maintain the same propulsive force. The individual coefficient of variation in the *SF* values was 2% on the average (60.2 ± 1.2 cycles·min^{-1}); thus, it could be tentatively suggested that a difference in *SF* lower than 2 cycles·min^{-1} between trials could be considered acceptable.

The assumption of a constant force is also supported by data of Samson et al. (2018) who demonstrated that the (estimated) propulsive forces generated by the hand in tethered and free-swimming are similar (except at sprint pace).

A final consideration regards the highest applied load in semi-tethered swimming tests (85% of F_T) where ka_{ST} is significantly lower than at the other loads (see Table 1). When average ka_{ST} is calculated over the entire load range (0 - 85%) it amounts to 37.7 kg·m^{-1} but when the highest load is excluded (0 - 75%) ka_{ST} amounts to 39.4 kg·m^{-1}, a value even closer to ka_{STfit} (e.g. 40.3 kg·m^{-1}). Whatever the reason for this difference, these findings indicate that care should be taken when attempting to assess active drag based on the “residual thrust method” when the applied load is too high. This observation is in agreement with recent data that indicate that with the velocity perturbation method (a semi-tethered test) active drag is probably underestimated when utilizing large external loads (Gonjo and Olstad, 2022).

Last but not least, a lack of practice with resistive swimming tests could be a reason why swimmers could not produce the same power output between swimming conditions, since the error in the measurement of the swim and tow velocities can vary depending upon the level of the swimmers (Hazrati et al., 2016, Hazrati et al., 2018). We recruited top sprinters for this study, and they were familiar with the experimental procedures, but care should be taken when applying the “residual thrust method” in less proficient swimmers. In this case, care should be taken also to increase the recovery time between trials, because differences in propulsive force (and hence in *SF*) among conditions could occur because of fatigue.

In conclusion, the present study demonstrates that active drag (front crawl swimming) is about 1.5 times larger than passive drag. The “residual thrust method” and the “planimetric method” led to similar results in the active drag quantification. Thus, the active drag estimation using an easy-to-use protocol based on full and semi-tethered swimming tests appears to provide reasonable results. Future studies should investigate whether this set of calculations could also be applied to the other strokes, for which the relationship between *kp* and *ka* is known (Gatta et al., 2015).

Conclusion

Quantifying resistive forces is of fundamental importance for an athlete / a swimming coach, since these deeply influence performance: the most successful swimmers are those able to maximize propulsive forces and minimize resistive forces. Thus, a swimmer with a good hydrodynamic asset (a low passive drag) who is also characterized by a low (active) drag has a definite advantage during a race. Since active drag depends, among the others, on the swimmer’s technical skills, the possibility to check the effects of training not only on propulsive but also on (active) resistive forces is determinant.

Whereas the model fitting utilized in this study requires a bit of computer knowledge, the simple set of calculations of the “residual thrust method” allows to estimate a swimmer’s active drag by using simple equations (e.g. $Da_{ST} = F_T - F_{ST}$) making the calculations post data collection friendly to the swimming coaches. Moreover, these experiments can be conducted in an ecological setting (the swimming pool) and require only basic instrumentation.

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Key points

- The active drag of a swimmer is about 1.5 times larger than the passive drag
- The planimetric method and the residual thrust method yield similar active drag values
- The active drag can be estimated by means of resisted swimming tests

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Supplementary Materials

Calibrations: Tethered and semi-tethered tests

The accuracy of the electro-mechanical device (Swim-Spektro) was tested during dynamic pulling on land. Velocity values (vST) were calibrated against data recorded using 2D video analysis. The device pulled an object at four constant speeds (0.5, 1.0, 1.5, 2.0 $m \cdot s^{-1}$) while a static camera (Hero4, GoPro, San Mateo, CA, USA, sampling rate 60 Hz, pixel resolution 1280 x 720) recorded the object transition on the sagittal plane (in a calibrated space 4 m in length); based on this calibration procedure, speed data, as determined using the Swim-Spektro ($vSpektro$), were corrected using the following linear equation: $vST = 1.0024 \cdot vSpektro + 0.006$ ($R^2 = 0.99$).

Force values (imposed loads) were calibrated against data recorded using a (previously calibrated) load cell (Globus Ergometer, Globus™, Codognè, Italy, range 0–2500 N, sampling rate

1000 Hz): a participant was asked to run on land at maximal speed while pulling imposed constant loads (30, 60, 90 N, $load_{Spektro}$) and with the load cell (Globus) positioned in series with the cable (between the participant and the Swim-Spektro device). Based on this calibration procedure, the imposed loads ($load_{Spektro}$) were corrected using the following linear equations: $load_{(Globus)} = 1.1831 \cdot load_{Spectro} + 30.467$ ($R^2 = 0.99$).

Calibrations: Passive drag measurements

Towing speed (v_{TOW}) was calibrated as described for the semi-tethered tests (Swim-Spektro device). Towing force was calibrated by pulling constant loads (26, 40, 68 N, $load_{Spektro}$) at a constant speed (1.0 $m \cdot s^{-1}$); in this case: $load_{(Globus)} = 1.0311 \cdot load_{Spektro} - 2.2117$ ($R^2 = 0.99$).