




A novel method for assessing added mass in front crawl swimming

Remi Carmigniani^a, Vittorio Coloretto^b, Thomas Brunel^a, Pietro Bosetto^b, Silvia Fantozzi^c, Matteo Cortesi^b, Paola Zamparo^{d,*}

^a LHSV, ENPC, Institut Polytechnique de Paris, EDF R&D, Chatou, France

^b Department for Life Quality Studies, University of Bologna, Bologna, Italy

^c Department of Electrical, Electronic and Information Engineering, University of Bologna, Bologna, Italy

^d Department of Neurosciences, Biomedicine and Movement Sciences, University of Verona, Verona, Italy

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ABSTRACT

During starts and turns, between and within laps, the swimmer's velocity is not constant; thus, besides the drag force, the swimmer experiences an additional (inertial) force. Some of the water around the swimmer is set in motion and this can be thought of as an added mass ($M_{A,a}$) the swimmer has to accelerate (in addition to body mass, M_0): the higher $M_{A,a}$, the higher the resistive and inertial forces that oppose the swimmer's motion during acceleration phases. This study introduces a novel method to determine $M_{A,a}$, consisting of a standing start maximal test. Sixteen male swimmers (526.1 ± 65.8 FINA Points) performed maximal sprints during which their instantaneous speed was assessed using an IMU positioned on their sacrum. The estimation of $M_{A,a}$ was based on the swimmer's maximum velocity (v_{max}) and acceleration time (τ), as determined using a standing start test, and the active drag coefficient (k_a) and mean propulsive force (F_p), as determined using the residual thrust method. On average $v_{max} = 1.73 \pm 0.11 \text{ m}\cdot\text{s}^{-1}$, $\tau = 1.14 \pm 0.11 \text{ s}$, $F_p = 146.8 \pm 20 \text{ N}$ and $k_a = 47.9 \pm 5.7 \text{ kg}\cdot\text{m}^{-1}$. $M_{A,a}$ in surface swimming ($28.7 \pm 15.2 \% M_0$) is similar to the added mass that can be determined in passive conditions underwater ($M_{A,p} = 25 \pm 3 \% M_0$) but presents a larger variability. This variability could not be attributed to the swimmer's technical level, e.g. the active to passive drag ratio: k_a/k_p , where $k_p = 26.6 \pm 3.3 \text{ kg}\cdot\text{m}^{-1}$ (determined using passive towing experiments).

1. Introduction

Swimming is a cyclic sport where (as in biking, running, rowing and kayaking) race velocity is determined by the balance between propulsive and resistive forces. Resistive forces are generally evaluated by asking the swimmer to maintain a constant average velocity; however, during races, the velocity fluctuates between and within laps. Swimmers start the race with a velocity that greatly exceeds their (average) swimming velocity, thanks to the push off from the starting blocks (as is the case after turns); changes in velocity can also be observed further away from the walls (e.g. Mauger et al., 2012; Simbaña-Escobar et al. 2018). Due to these fluctuations in velocity, besides the drag force, the swimmer experiences an additional (inertial) force: some of the water around the swimmer is set in motion and this can be thought of as an added mass the swimmer has to accelerate, in addition to body mass (Vogel, 1994, Caspersen et al., 2010). To consider the fluctuations in

velocity between cycles, we filtered the instantaneous velocity $V(t)$ by applying a moving average integration window as:

$$v(t_i) = \frac{1}{T} \int_{t_i - \frac{T}{2}}^{t_i + \frac{T}{2}} V(t) dt \quad (1)$$

where $v(t_i)$ is the filtered velocity and T the duration of a cycle. The Newton's Second Law on the swimmer system in the direction of the race can then be written as:

$$F_p = F_{D,a} + (M_0 + M_{A,a}) \frac{dv}{dt} \quad (2)$$

where F_p is the mean propulsive force, $F_{D,a}$ is the mean active drag, M_0 is the swimmer's body mass, $M_{A,a}$ is the added mass (of water) in active conditions, and v is the swimmer's mean velocity. Note that, in this equation, the added mass is assumed to perceive the same acceleration

* Corresponding author at: Department of Neurosciences, Biomedicine and Movement Sciences, University of Verona, Verona 37131, Italy.

E-mail addresses: remi.carmigniani@enpc.fr (R. Carmigniani), vittorio.coloretto2@unibo.it (V. Coloretto), thomas.brunel@enpc.fr (T. Brunel), pietro.bosetto@studenti.univr.it (P. Bosetto), silvia.fantozzi@unibo.it (S. Fantozzi), m.cortesi@unibo.it (M. Cortesi), paola.zamparo@univr.it (P. Zamparo).

¹ ORCID: 0000-0002-6919-6721.

as the swimmer's mass, as we assume the water in the swimming pool is at rest.

When swimming at a constant velocity, Eq. (2) reduces to:

$$F_p = F_{D,a} \quad (3a)$$

Assuming that $F_{D,a}$ increases with the square of swimming speed:

$$F_{D,a} = k_a v^2 \quad (3b)$$

where k_a is the active drag coefficient; Eq. (3a) can then be written as:

$$F_p = k_a v^2 \quad (3c)$$

According to Eq. (2), the higher the added mass, the higher the (resistive and inertial) forces that oppose the swimmer's motion during acceleration. Knowing the swimmer's $M_{A,a}$ has, thus, important applications in competitive swimming. Swimming literature, however, mainly focuses on evaluating the active drag for constant velocity swimming (where Eq. (3b) applies) because measuring the active added mass is not an easy task.

To the authors' knowledge, Klauck (1999) was the first to discuss the question of added mass in swimming; in passive towing experiments, it was estimated to range from 47 to 110 % of the displaced fluid mass. To estimate passive drag on a deceleration test, Kjendlie & Stallman (2008) suggested using a 50 % coefficient. Later on, Caspersen et al. (2010) evaluated the added mass of fully submerged swimmers (standing on an oscillating bar, in an extended gliding position) to be around 25 % of their body mass. In all these studies the swimmers were "passive", so let's define the added mass in these conditions as $M_{A,p}$.

To our knowledge, no studies attempted to quantify, so far, the added mass during actual surface swimming ($M_{A,a}$) but a recent study on kayaking by Prétot et al. (2022) proposed a novel method to investigate the force balance in unsteady conditions; it consists of a standing start test and is based on the analysis of the time course of velocity in the acceleration phase (up to maximal velocity). When the added mass is known (and in kayaking, it can be evaluated based on the length and width of the kayak), this test can be used to assess the active drag and the propulsive force ($F_{D,a}$ and F_p in Eqs. (2) and (3)); conversely, if $F_{D,a}$ and F_p are known, this test can be used to evaluate $M_{A,a}$.

In this study, we used the standing start method to evaluate $M_{A,a}$ while swimming at the surface, by using F_p or $F_{D,a}$ data (as determined using the "residual thrust" method). We then tested the possibility of using the standing start test to evaluate $F_{D,a}$ and F_p (by using a passive added mass = 25 % BM, as proposed by Caspersen et al., 2010).

However, we expected active added mass to be larger than passive added mass because the swimming movements could, hypothetically, set more water in motion compared to passive conditions (this was our first hypothesis). In addition, we wanted to test a second hypothesis (put forward by Caspersen et al. 2010) that $M_{A,a}$ depends not only on the mass (and shape) of a swimmer (as is the case for $M_{A,p}$) but also on his/her technique, which can be estimated based on the active to passive drag ratio (e.g. highly skilled swimmers are expected to swim with an active drag that is closer to their passive drag, compared to swimmers with poorer technique).

2. Methods

2.1. Participants

Sixteen male sprinters (age: 22.7 ± 3.0 years, stature: 1.77 ± 0.05 m, body mass 74.8 ± 7.9 kg) were recruited for the study. They trained a minimum of twice a week and performed between 27.5 and 23.1 s on a 50-m front crawl (performance level: 84 ± 4 % of the world record in 50-m front-crawl and 526.1 ± 65.8 FINA Points). Participants 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: 0335732) and conducted in accordance with the principles of the Declaration of Helsinki.

2.2. Experimental design

This is an observational research study. Full-tethered and semi-tethered tests, passive towing tests and standing start sprints were carried out with the aim to determine passive drag ($F_{D,p}$), active drag ($F_{D,a}$), propulsive force (F_p) and active added mass ($M_{A,a}$).

All swimmers wore a training swimsuit and 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 in a 25 m indoor swimming pool (1.7 m depth) for one swimmer at a time and the order in which tests were performed was randomized across swimmers.

2.3. Methodology

2.3.1. Passive drag measurements and "planimetric" method

To evaluate passive drag, swimmers performed five passive towing trials at the water surface, in a streamlined position, at a constant velocity (v_{TOW}) of 1.0, 1.3, 1.6, 1.9 and 2.2 m s^{-1} .

Passive drag values ($F_{D,p}$) were measured using an electro-mechanical device composed of a low-voltage isokinetic engine (Swim-Spekro, Talamonti Spa, Ascoli Piceno, Italy) at the imposed towing velocities. The average force between 10 and 20 m from the wall was used in the following analysis (for further details, see Scurati et al., 2019). For each swimmer, $F_{D,p}$ was fitted to:

$$F_{D,p} = k_p v_{TOW}^2 \quad (4)$$

to obtain k_p (the passive drag coefficient). We thus assumed that passive drag increases with the square of speed.

According to the "planimetric" method the active drag coefficient (in male swimmers and in front crawl) can be estimated as: $k_{a,PL} = 1.5k_p$ (see Gatta et al., 2015). This allows to get a first evaluation of active drag as:

$$F_{D,aPL} = 1.5k_p v^2 \quad (5)$$

2.3.2. Tethered and semi-tethered tests ("residual thrust" method)

Swimmers performed tethered and semi-tethered tests to evaluate active drag using the "residual thrust" method (for details see Cortesi et al., 2024, and Supplementary materials). Swimmers started with a full-tethered all-out trial to evaluate their full tethered force (F_T). In this case, swimmers were attached to the wall through a non-elastic (steel) cable, thus $v_T = 0$ and Eq. (2) can be written as:

$$F_{P,T} = F_T \quad (6)$$

where $F_{P,T}$ is the propulsive force generated during the full tethered test. Full tethered force (F_T) was evaluated using a load cell (GlobusTM, Codognè, Italy).

Swimmers then performed the semi-tethered tests: they were asked to swim at maximal intensity while pulling imposed loads set as 25, 50 and 75 % of their previously measured F_T . To avoid accumulation of fatigue, these tests were separated by a minimum of 3 min of active recovery and the effort was limited to about 10 s. The loads (F_{ST}) were imposed and the velocity of the swimmers (v_{ST}) was measured using the Swim-Spekro device. For some participants, at the highest loads, the velocity decreased during the trial; in these cases, only the steady state phase was considered (at least 5 cycles). When the velocity of the swimmer is steady, Eq. (2) yields:

$$F_{P,ST} = F_{ST} + k_{a,ST} v_{ST}^2 \quad (7)$$

where $F_{P,ST}$ is the propulsive force generated during the semi-tethered test and F_{ST} is the imposed load. The procedures for the calibration of

the electromechanical device and of the load cell are described in Cortesi et al. (2024).

Typical results for a given swimmer are illustrated in Fig. 1: as the imposed load increases (F_{ST}) the swimmer velocity decreases (v_{ST}); the crosses indicate the values of active drag ($F_P - F_{ST}$). Passive drag (open squares and dotted line) and active drag as obtained using the “planimetric” method (dashed line) are represented in Fig. 1 as well.

During the full and semi-tethered tests stroke frequency (SF) was also recorded since the constant mean thrust assumption is considered valid ($F_{P,ST} = F_{P,T}$) when the stroke frequency does not vary significantly for the different loads. SF was assessed using two IMUs (Movella DOT, Movella, Henderson, NV, USA) attached to the swimmer’s wrists; data were elaborated following the procedure proposed by Fantozzi et al. (2022). SF was then computed as average over 10 S cycles, excluding the first, for both upper limbs.

2.3.3. Standing start tests (maximal sprints)

Standing start trials were performed to evaluate the swimmer’s active drag using one IMU (Movella DOT, Movella, Henderson, NV, USA) attached to their sacrum (see supplementary materials for details).

Firstly, participants were asked to remain stationary in a prone buoyant position for five seconds to more easily identify the starting point and then to sprint as fast as possible (front-crawl, avoiding breathing and without pushing against the wall), for about 10 S cycles; the standing starts were repeated three times (separated by a minimum of 3 min of active recovery to avoid fatigue).

During this test, it was assumed that swimmers verified Eq. (2) with a constant propulsive force and starting with no initial velocity ($v(t=0) = 0$). The velocity then evolves with time as:

$$v(t) = v_{max} \tanh\left(\frac{t}{\tau}\right) \quad (8)$$

where:

$$v_{max} = \sqrt{F_P/k_a} \quad (9)$$

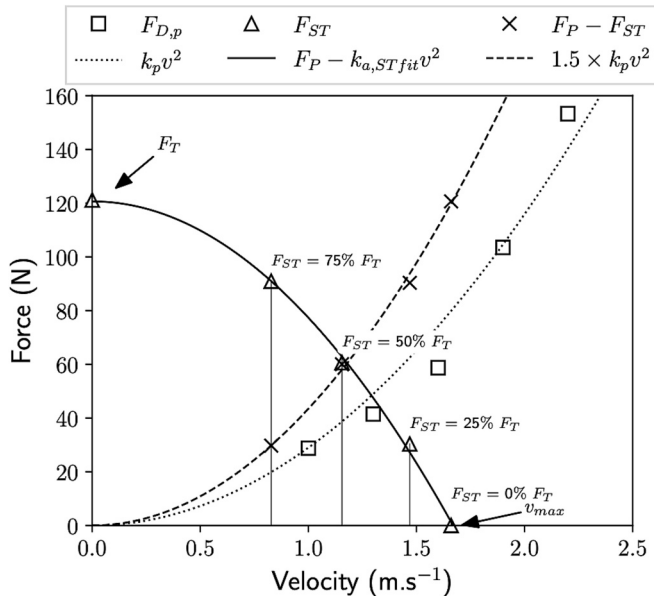


Fig. 1. Estimation of active drag using the residual thrust method (crosses = $F_P - F_{ST}$). The triangles indicate the values of semi-tethered force ($F_{ST} = 25, 50$ and $75\% F_T$) and full tethered force (F_T) at the corresponding velocities; the value of maximum velocity with no load is that reached during the standing start test and the continuous line fits these values. Passive drag is also presented (open squares) with the corresponding fitting (dotted line). The dashed line indicates the active drag values as determined using the planimetric method. See text for details.

is the maximum velocity reached during the standing start trial and:

$$\tau = (M_0 + M_{A,a}) / \sqrt{k_a F_P} \quad (10)$$

is the characteristic acceleration time of the swimmer. The measured velocity was fitted to Eq. (8) and the values of v_{max} and τ were determined and used in further analysis (see supplementary materials and Fig. 2).

In the standing start tests, the thrust ($F_{P,SS}$) and the speed-specific drag ($k_{a,SS}$) can be calculated based on maximum velocity (v_{max}) and acceleration time (τ), by assuming an added mass (passive) = 25 % BM, as proposed by Caspersen et al. (2010). The mean propulsive force is evaluated as:

$$F_{P,SS} = (M_0 + M_{A,p}) \frac{v_{max}}{\tau} \quad (11)$$

and the active drag coefficient as:

$$k_{a,SS} = (M_0 + M_{A,p}) / v_{max} \tau \quad (12)$$

2.3.4. Evaluation of active drag (speed specific drag)

The active drag was calculated by means of four different methods:

1. The “planimetric” method, using the passive towing tests. In this case the speed-specific drag ($k_{a,PL}$) is calculated as $k_{a,PL} = 1.5 k_p$ (Gatta et al. 2015)
2. The “residual thrust” method, assuming a constant mean propulsive force equal to the full tethered force ($F_{P,ST} = F_{P,T} = F_T$). In this case the speed-specific drag ($k_{a,ST}$) is defined as the mean of four ($F_T - F_{ST}$)/ v_{ST}^2 values (i.e. $k_{a,ST} v_{ST}^2 = F_T - F_{ST}$, see eq. (7): three values at 75, 50 and 25 % of F_T and one value corresponding to the maximum velocity of the standing start test (where $v_{ST} = v_{max}$ and $F_{ST} = 0$).
3. The “fitted residual thrust” method. In this case, the thrust ($F_{P,ST,fit}$) and the speed-specific drag ($k_{a,ST,fit}$) are estimated given the imposed load F_{ST} and measured speed v_{ST} on five different conditions: full tethered force (one value, $v_{ST} = 0$ and $F_{ST} = F_T$), semi-tethered swimming (three values at 75, 50 and 25 % of F_T) and standing start maximum velocity (one value, $v_{ST} = v_{max}$ and $F_{ST} = 0$). See supplementary materials for further details.
4. The “standing start” method. In this case, $k_{a,SS}$ is calculated based on Eq. (12), using the passive added mass coefficient ($C_{A,p} = 25 \pm 3\%$) reported by Caspersen et al. (2010)

2.3.5. Evaluation of added mass (active added mass coefficient)

Finally, the active added mass ($M_{A,a}$) was estimated by assuming a known thrust (F_P) or active drag coefficient (k_a) and rearranging Eqs. (11) and (12) as:

$$M_{A,a} = \frac{F_P \tau}{v_{max}} - M_0 \quad (13)$$

$$M_{A,a} = k_a v_{max} \tau - M_0. \quad (14)$$

For these calculations we used the values assessed by means of the full-tethered test ($F_P = F_T$: $M_{A,a1}$) and by means of the residual thrust methods: $F_P = F_{P,ST,fit}$: $M_{A,a2}$; $k_a = k_{a,ST,fit}$: $M_{A,a3}$ and $k_a = k_{a,ST}$: $M_{A,a4}$. The relative added mass (C_A) can then be calculated by dividing $M_{A,a}$ by the subject’s body mass (M_0).

A flowchart summarising all methods and calculations is reported in Fig. 3.

2.3.6. Evaluation of the swimmer’s technical level

The ratio between the active and passive drag coefficients (k_a/k_p), sometimes called the technique drag index (e.g. Kolmogorov & Duplishcheva, 1992; Kjiendlie and Stallmann 2008), was utilized as an index of the swimmer’s technical level.

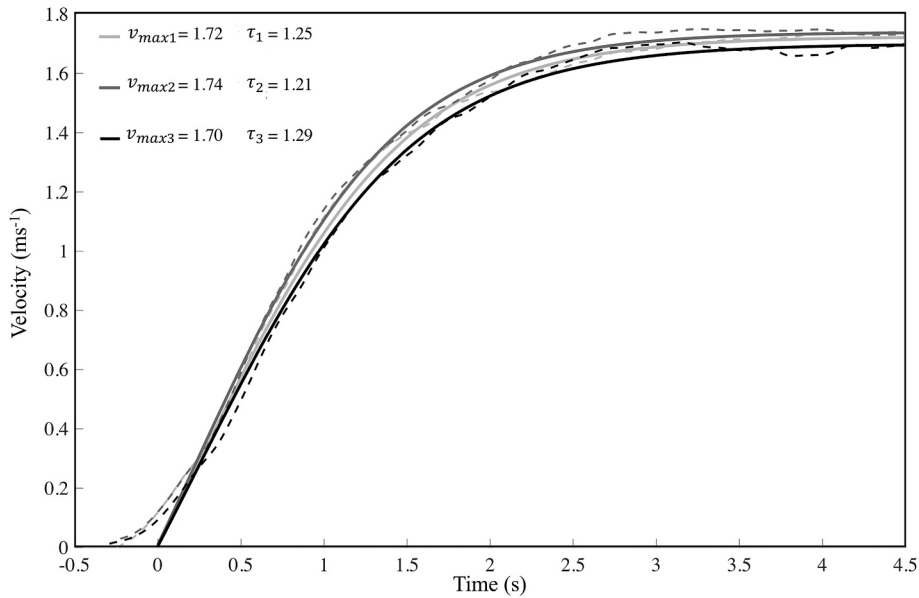


Fig. 2. Time course of velocity during the three standing start tests in a given swimmer. Velocity data (dotted lines) are filtered and then fitted (continuous lines) to evaluate maximum velocity (v_{max}) and the acceleration time (τ). See Supplementary materials for details.

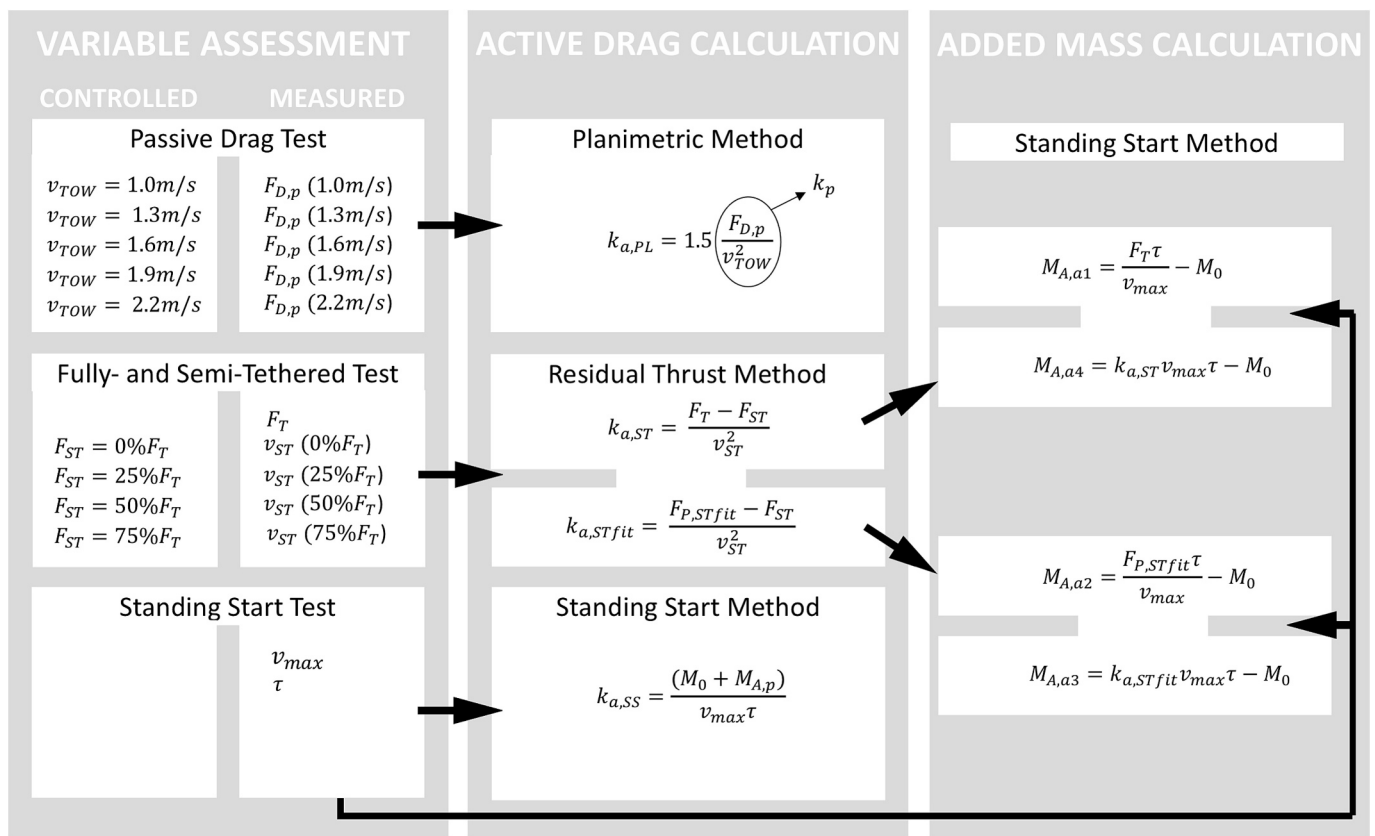


Fig. 3. Representative flow charts for active drag and added mass calculation. v_{TOW} : towing velocity; $F_{D,p}$: passive drag force; $k_{a,PL}$: active drag coefficient calculated by planimetric method; F_{ST} : semi-tethered force; F_T : full tethered force; swimming velocity corresponding to specific semi-tethered force; v_{ST} : swimming velocity corresponding to semi-tethered force; $k_{a,ST}$: active drag coefficient calculated by residual thrust method; $k_{a,STfit}$: active drag coefficient calculated by fitting data of semi-tethered tests; $F_{P,STfit}$: propulsive force – thrust force calculated by fitting data of semi-tethered tests; v_{max} : maximum velocity reached during the standing start trial; τ : acceleration time of the swimmer; $k_{a,SS}$: active drag coefficient calculated by standing start method; M_0 : body mass; $M_{A,p}$: added mass in passive swimming; $M_{A,a1}$: added mass in active swimming using F_T ; $M_{A,a2}$: added mass in active swimming using $F_{P,STfit}$; $M_{A,a3}$: added mass in active swimming using $k_{a,STfit}$; $M_{A,a4}$: added mass in active swimming using $k_{a,ST}$.

2.4. Statistical analysis

Data are presented as mean \pm standard deviation. All variables were tested for normality using the Shapiro–Wilk test. To analyze differences between methods for propulsive force, drag, and stroke frequency, a repeated-measures one-way analysis of variance (ANOVA) was performed followed by Bonferroni post-hoc corrections, where appropriate. For variables that did not meet normality assumptions (added mass), the non-parametric Friedman test was applied.

Pearson's correlation (r) analysis was performed to investigate the relationships between $M_{A,a}$ and k_a/k_p ; the magnitude of r was rated according to Hopkins et al. (2009).

Statistical significance was set at $\alpha = 0.05$. All analyses were performed using JASP (JASP Team, 2020, Amsterdam, the Netherlands).

3. Results

The passive drag coefficient (k_p) was $26.6 \pm 3.3 \text{ kg m}^{-1}$ and the active drag coefficient estimated using the “planimetric” method ($k_{a,PL}$) was $39.9 \pm 5.0 \text{ kg m}^{-1}$. During the standing start tests, average v_{max} was $1.73 \pm 0.11 \text{ m s}^{-1}$ and average τ was $1.14 \pm 0.11 \text{ s}$.

The values of SF (strokes min^{-1}) did not change across conditions in the full-, semi-tethered and free-swimming conditions as shown by the ANOVA main effect ($F_{4,60} = 0.859$; $p = 0.494$; $\eta^2 = 0.054$): 57.1 ± 5.5 (F_T); 57.1 ± 6.0 (75 % F_T); 57.0 ± 5.3 (50 % F_T); 57.1 ± 5.9 (25 % F_T); 57.9 ± 5.8 (0 % F_T).

The values of propulsive force, as determined using the different methods, are reported in Fig. 4. No significant differences were detected among F_T ($147.9 \pm 20.5 \text{ N}$), $F_{P,STfit}$ ($146.8 \pm 20 \text{ N}$) and $F_{P,SS}$ ($143.8 \pm 24.1 \text{ N}$) using the one-factor ANOVA with repeated measures ($F_{2,30} = 0.914$; $p = 0.412$; $\eta^2 = 0.057$).

The active drag coefficients, as determined using the different methods, are reported in Fig. 5. A significant main effect between k_a values was observed in the one-factor ANOVA with repeated measures ($F_{3,45} = 17.860$; $p < 0.001$; $\eta^2 = 0.544$): Bonferroni post hoc test reveals $k_{a,PL}$ significantly lower than $k_{a,ST}$ ($p < 0.001$; CI: -13.217 – 5.397), $k_{a,STfit}$ ($p < 0.001$; CI: -11.895 – 4.075) and $k_{a,SS}$ ($p < 0.001$; CI: -11.693 – 3.873). No significant differences were observed between $k_{a,SS}$ ($47.7 \pm 4.5 \text{ kg m}^{-1}$), $k_{a,ST}$ ($49.2 \pm 6.3 \text{ kg m}^{-1}$) and $k_{a,STfit}$ ($47.9 \pm 5.7 \text{ kg m}^{-1}$).

The active added mass coefficients ($C_{A,a}$) were close to the passive value of Caspersen et al., (2010) ($C_{A,p} = 25 \pm 3 \%$) but with a larger variability: $C_{A,a1} : 30 \pm 15\%$; $C_{A,a2} : 29 \pm 15\%$; $C_{A,a3} : 26 \pm 15\%$;

$C_{A,a4} : 30 \pm 17\%$.

No differences were observed between $M_{A,p}$ and any of the $M_{A,a}$ values. Even if the main effect of the Friedman test was significant ($\chi^2_{(16,4)} = 11.75$; $p = 0.019$; $W = 0.184$), the Conover's post hoc analysis indicate a difference only between $M_{A,a1}$ and $M_{A,a3}$ ($p = 0.022$).

The individual values of added mass are reported in Table 1; these data indicate that the variability in the values of $M_{A,a}$ is mainly attributable to inter-subject differences, since the intra-individual variability is rather low (the errors are computed using the propagation of uncertainty method).

No significant association was observed between $M_{A,a}$ (all four values) and the active/passive drag ratio (calculated either as $k_{a,ST}/k_p$ or $k_{a,STfit}/k_p$) with $0.10 < r < 0.37$ (small or moderate correlation).

4. Discussion

In this study, active drag, propulsive force and “active” added mass are estimated using a novel method, the standing start test. While active drag and propulsive forces were often investigated in the literature, few research papers discussed the added mass in swimming and none, to the authors' knowledge, evaluated the added mass in active swimming conditions.

Data reported in this study indicate similar values of added mass in passive (underwater) and active (surface swimming) conditions, confuting the first hypothesis. In addition, we rejected also the second hypothesis: the inter-subject differences in $M_{A,a}$ are not related to differences in technical level (as assessed based on the k_a/k_p ratio).

4.1. Active and passive drag

The passive drag values reported in this study are consistent with those reported in the literature (for a review see Havriluk, 2005; Scurati et al., 2019). Regarding active drag, while some studies report active drag equal or even lower than passive drag (Kolmogorov & Duplishcheva, 1992; Toussaint et al., 1988), many others indicate that the former is larger than the latter (Cortesi et al., 2024; Formosa et al., 2012; Gatta et al., 2015; Hazrati et al., 2016; Narita et al., 2017, di Prampero, 1986, Takagi et al., 1999, Shimonagata et al., 1999) and this is the case also for the methods utilized in this study to determine $k_{a,ST}$ and $k_{a,STfit}$.

In the present work, we introduce a further (novel) method to evaluate the active drag coefficient based on a standing start test ($k_{a,SS}$). Using the added mass values proposed by Caspersen et al. (2010), we got values of $k_{a,SS}$ comparable to $k_{a,ST}$ and $k_{a,STfit}$; these results once again

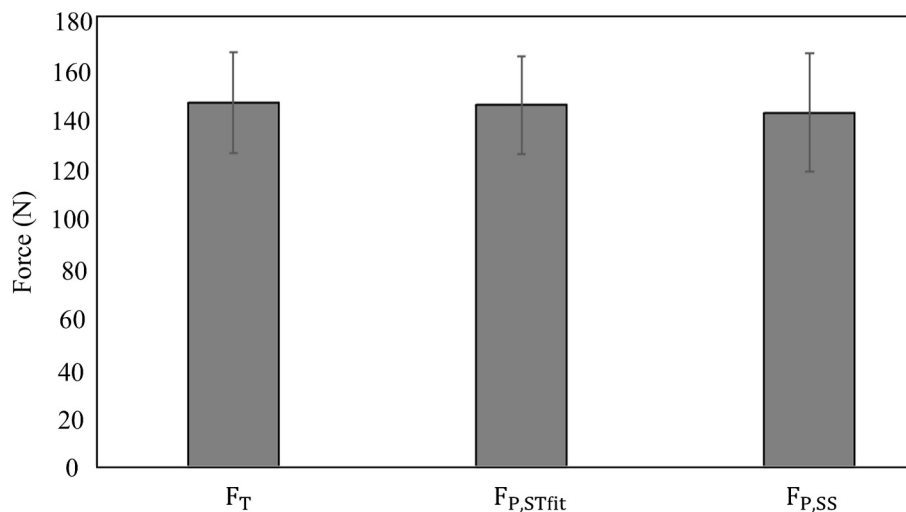


Fig. 4. Propulsive force based on the different methods. F_T : full tethered force; $F_{P,STfit}$: propulsive force calculated by fitting data of semi-tethered tests; $F_{P,SS}$: propulsive force calculated based on the standing start tests. Data are means \pm SD. See Fig. 3 and text for details.

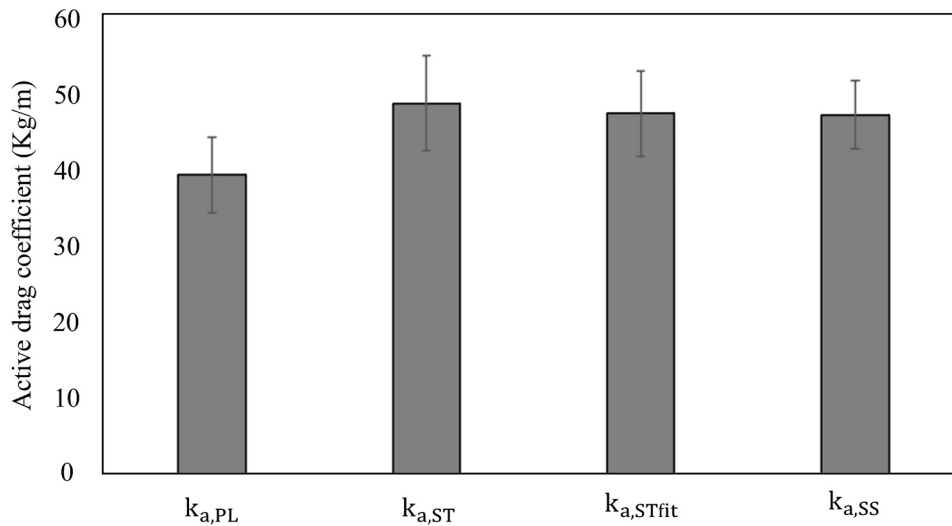


Fig. 5. Active drag coefficients as determined using different methods. $k_{a,PL}$: active drag coefficient calculated by planimetric method; $k_{a,ST}$: active drag coefficient calculated by residual thrust method; $k_{a,STfit}$: active drag coefficient calculated by fitting data of semi-tethered tests; $k_{a,SS}$: active drag coefficient calculated by standing start method. Data are means \pm SD. See Fig. 3 and text for details.

Table 1

Individual values of passive ($M_{A,p}$) and active ($M_{A,a}$) added mass. $M_{A,a}$ was estimated based on values of v_{max} and τ (as assessed during the standing start tests) and values of active drag coefficient ($k_{a,ST}$ and $k_{a,STfit}$) or propulsive force (F_T and $F_{P,STfit}$) as assessed by means of full- and semi-tethered tests. Data are means \pm SD.

	$M_{A,p}$ (25 %BM) (kg)	$M_{A,a1}$ (F_T) (kg)	$M_{A,a2}$ ($F_{P,STfit}$) (kg)	$M_{A,a3}$ ($k_{a,STfit}$) (kg)	$M_{A,a4}$ ($k_{a,ST}$) (kg)
S1	18.8 \pm 2.3	11.5 \pm 0.6	8.1 \pm 0.5	7.5 \pm 0.6	19.1 \pm 2.6
S2	17.3 \pm 2.1	12.4 \pm 1.0	10.6 \pm 1.0	9.9 \pm 1.0	14.8 \pm 1.9
S3	20.5 \pm 2.5	31.2 \pm 1.1	30.9 \pm 1.4	27.6 \pm 1.6	28.7 \pm 1.7
S4	15.5 \pm 1.9	42.1 \pm 1.5	41.5 \pm 2.2	38.4 \pm 2.7	40.2 \pm 2.9
S5	21.0 \pm 2.5	40.6 \pm 3.0	37.4 \pm 3.1	42.0 \pm 4.1	53.4 \pm 6.0
S6	21.0 \pm 2.5	16.6 \pm 0.6	19.4 \pm 1.0	13.6 \pm 0.9	6.4 \pm 0.5
S7	21.0 \pm 2.5	16.5 \pm 0.7	15.8 \pm 0.7	13.2 \pm 0.8	15.6 \pm 1.0
S8	19.3 \pm 2.3	23.8 \pm 1.1	23.6 \pm 1.5	17.6 \pm 1.5	18.5 \pm 1.5
S9	16.5 \pm 2.0	16.5 \pm 1.3	16.1 \pm 1.2	15.2 \pm 1.2	16.3 \pm 1.3
S10	19.8 \pm 2.4	43.4 \pm 2.4	43.7 \pm 3.4	37.3 \pm 3.8	36.9 \pm 3.4
S11	17.8 \pm 2.1	13.5 \pm 0.7	11.7 \pm 0.8	7.0 \pm 0.7	13.3 \pm 1.7
S12	15.0 \pm 1.8	16.6 \pm 1.1	14.7 \pm 1.0	16.8 \pm 1.2	22.7 \pm 2.0
S13	19.8 \pm 2.4	15.1 \pm 0.8	17.2 \pm 1.1	12.4 \pm 1.0	6.8 \pm 0.6
S14	18.3 \pm 2.2	14.5 \pm 0.8	14.4 \pm 0.8	11.9 \pm 0.7	13.1 \pm 1.1
S15	17.3 \pm 2.1	15.9 \pm 0.9	13.5 \pm 0.8	15.0 \pm 1.1	22.9 \pm 2.2
S16	20.5 \pm 2.5	28.4 \pm 4.3	30.2 \pm 4.6	25.0 \pm 4.0	20.2 \pm 3.2

For $M_{A,p}$ the SDs refer to the 3% variability in the estimates of passive added mass reported by Caspersen et al. (2010).

confirm that active drag is larger than passive drag. This method (standing start test) is particularly interesting as it can be implemented in practice with low-cost equipment (such as an IMU attached to the sacrum, as here) or any velocity measurement system (Mooney et al., 2016).

As for the residual thrust method, the standing start method relies on the assumption that the mean propulsive force ($F_{P,SS}$) is constant during the entire acceleration phase of the swimmer. This is supported by the fact that $F_{P,SS}$ is not significantly different from F_T and $F_{P,STfit}$. However, this will require further testing using, for instance, instrumented paddles as presented in Brunel et al. (2023).

4.2. Added mass

Coupling the residual thrust method and the standing start test, we proposed a novel method to estimate the active added mass of a swimmer.

The active added mass coefficient ($C_{A,a} = 28.7 \pm 15.2$ % of body mass, average of all $C_{A,a}$ values) is similar to that reported by Caspersen

et al. (2010) ($C_{A,p} = 25$ % of body mass, in an extended gliding position and with the body fully submerged) but presents a larger variability. The individual values reported in Table 1 show that, in our cohort, the passive added mass ($M_{A,p}$) ranges from 15 to 21 kg while the active added mass ranges from 11 to 43 kg ($M_{A,a1}$), from 8 to 44 kg ($M_{A,a2}$), from 7 to 42 kg ($M_{A,a3}$), and from 6 to 53 kg ($M_{A,a4}$); this latter case (where calculations are based on values of $k_{a,ST}$, resulting from a simple average operation, without fitting) being that with the larger scatter.

Whereas inter-subject differences in $M_{A,p}$ mainly depend on the anthropometric characteristics of a swimmer (see Caspersen et al. 2010), the inter-subject differences in $M_{A,a}$ could be attributed to his/her technical skills. We hypothesized that more proficient swimmers could be characterized by lower $M_{A,a}$ values because active drag tends to be lower in competitive swimmers, or after a training period (Pendergast et al., 2005).

However, we did not observe any significant relationship between $M_{A,a}$ and the k_a/k_p ratio, an index that is expected to be higher in less experienced swimmers (e.g. Kolmogorov & Duplishcheva, 1992; Kjiendlie and Stallmann 2008). The reason of the inter-subject

variability in active added mass thus deserves further studies.

The variability in the $M_{A,a}$ values could partially be attributed to the fact that the standing start is a complex test to perform, and minimal technical errors can significantly affect the results. Therefore, the recommendation is to use this test only with high-level swimmers (for whom this test requires minimal familiarization, as it is commonly employed in sprint development training), or at least to ensure thorough familiarization with the test to stabilize the result. In addition, a complete recovery between tests must be provided to avoid the effects of fatigue on force production.

5. Conclusions

The active added mass coefficient is similar to that reported by Caspersen and coworkers in an extended gliding position and with the body fully submerged, but presents a larger variability. The reason for the inter-subject differences in active added mass does not seem to be related to the swimmer's technical level (e.g. the k_a/k_p ratio).

6. Previous presentation of material

None. The results represented in the manuscript have not previously been presented or published.

CRedit authorship contribution statement

Remi Carmigniani: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Vittorio Coloretto:** Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Thomas Brunel:** Writing – review & editing, Software, Data curation. **Pietro Bosetto:** Writing – review & editing, Methodology, Data curation. **Silvia Fantozzi:** Writing – review & editing, Software, Methodology, Formal analysis, Data curation. **Matteo Cortesi:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Paola Zamparo:** Writing – review & editing, Writing – original draft, Supervision, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jbiomech.2025.112816>.

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