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Comparison of the Active Drag and Passive Drag Coefficients at the same Swimming Speed Through Experimental Methods

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Abstract

Studies about drag in swimming usually report or put the focus on its absolute value. However, it is being claimed that the drag coefficient better represents the hydrodynamic profile of a swimmer. Drag is strongly dependent on speed. Thus, increases in speed will lead to increases in drag. This could lead to misleading interpretations since drag is the water resistance that makes the swimmers' displacement difficult. Conversely, the drag coefficient is less dependent on speed, which can be seen as a more appropriate measure of the swimmers' hydrodynamic profile. This study used a complete experimental methodology (experimental and cross-sectional study) to determine the resistive forces in crawl swimming at the same speed (i.e., 1.00, 1.05, 1.10 m/s, etc.). In 10 proficient non-competitive adult swimmers (seven men and three women), the drag coefficient (C_D) was compared and the difference between using the technical drag index (TDI) with drag (D, passive or active) or with its respective C_D 's. Measurements of active drag (D_A), passive drag (D_P) and C_D (C_{DA} and C_{DP}) were carried out. The TDI was calculated as a measure of swimming efficiency and the frontal surface area (FSA) obtained in active conditions. The active FSA was 20.73 ± 5.56% greater than the passive FSA (large effect size), the propulsion was 58.29 ± 69.61% greater than drag and C_{DA} was 24.60 ± 46.55% greater than C_{DP} (moderate effect size). TDI was significantly lower, but with a small effect size when measured with C_D values compared to drag. TDI_D vs TDI_{CD} revealed strong agreement (> 80% of plots were within IC95). This study concludes that proficient swimmers presented a C_{DA} greater than the CDP, but with strong agreement between them, probably due to FSA during active conditions. C_D data appears to be a more absolute indicator of drag than TDI.

Keywords: *human body, practical methodology, resistive forces, biomechanics, technique*

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Introduction

Swimming speed depends on the interaction between propulsive and resistive forces (also known as drag) (Toussaint and Beek, 1992). Propulsive forces refer to the force generated by the swimmer through the actions of the upper and lower limbs to promote forward motion (Berger, 1999). Conversely, drag is the water resistance to a swimmer moving through water (Vogel, 1994). This can be expressed by Newton's equation as:

$$D = \frac{1}{2} \cdot v^2 \cdot \rho \cdot S \cdot C_d \qquad (1)$$

where D is the drag force (in N), ρ is the water density (in kg/m^3), υ is the swimming speed (in m/s), S is the projected frontal surface area (FSA) of swimmers (in m^2) and C_D is the drag coefficient (changing according to shape, orientation and Reynolds number). Drag can be passive (D_P – force produced during the displacement of a towed body) (Pendergast et al., 2006), or active (D_A – water resistance induced in a body during swimming) (Kolmogorov and Duplishcheva, 1992).

Literature has been reporting that D_A is about 1.5 to 2.0 times larger than D_P in the front-crawl stroke (Cortesi et al., 2024; Gatta et al., 2016; Narita et al., 2017). If, on one side, the towing test can be considered the gold standard for measuring D_P, several methods are used to measure or estimate D_A (Kolmogorov and Duplishcheva, 1992; Narita et al., 2017). For instance, in a recent study, full and semi-tethered tests were carried out based on the residual thrust method (Cortesi et al., 2024). However, one can still argue that: (i) any method that doesn't allow the swimmers to swim "freely" may provide some mechanical constraint, and; (ii) this comparison must be done at the same speed. Additionally, new trends in swimming hydrodynamics highlighted that the drag coefficient (C_D; passive – C_{DP}; or active – C_{DA}) should be the parameter to consider when analyzing the swimmers' hydrodynamic profile (Morais et al., 2024). This occurs because the C_D is less dependent on speed than drag (Kolmogorov and Duplishcheva, 1992; Vilas-Boas et al., 2010). As far as our understanding goes, there is still scarce evidence about the comparison between the C_{DP} and C_{DA} at the same speed which can bring new insights about the swimmers' hydrodynamics.

Additionally, the technique drag index (TDI) is considered a proxy of swimming efficiency by considering the ratio of D_A to D_P (Kjendlie and Stallman, 2008). For instance, if two swimmers present a similar D_P, the one with a smaller D_A could be considered as having a better swimming technique (Barbosa et al., 2013; Kjendlie and Stallman, 2008). Comparing the TDI based on drag and based on the C_D will also give insights about the importance of using the C_D as the most indicated parameter of swimming hydrodynamics.

Therefore, the aim of this study was to compare the C_{DP} with the C_{DA} in the front-crawl stroke at the same speed and understand the difference of using the TDI with drag (passive or active) or with their respective C_D's. It was hypothesized that the C_{DA} would be meaningfully greater than the C_{DP} at the same speed, and that this difference would be like the one verified between propulsion and drag. Also, the TDI based on drag would be meaningfully greater than when based on the C_D.

Methods

Participants

The sample was composed of 10 adult proficient non-competitive swimmers (seven males and three females: 20.7±1.9 years, 71.7±8.6 kg of body mass, 175.1±7.8 cm of height, 174.6±8.0 cm of arm span, and a 25 m performance of 20.25±2.72s in a 25 m sprint test with an in-water push-off start). Participants were engaged in a twice-weekly (three hours) swimming lesson program. All had a background in swimming with 4.1±2.2 years of practice. All procedures were in accordance with the Declaration of Helsinki regarding human research. A written consent form was provided and the Polytechnic Ethics Committee approved the research design (N.º 72/2022).

Research Design

After a 10-minute in-water warm-up and 5-minute dry-land stretching, the participants were invited to perform three maximal trials of 25-m in front-crawl stroke with a push-off start. The trials were spaced by an interval of 30 minutes. The fastest trial was used for further analysis. Only data between the 10th and 20th meter marks were analyzed to avoid the advantage gained in the push-off start. In active (while swimming) and passive (towed) conditions, the participants were instructed to perform non-breathing strokes or to hold their breath after maximal inspiration. Figure 1 depicts an example of a swimmer being towed (i.e., passive drag).

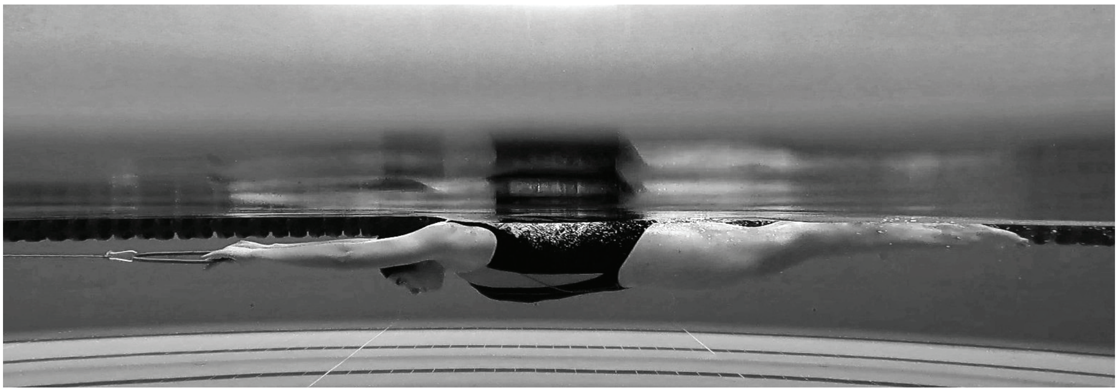

Figure 1. Illustration of a swimmer being towed for the passive drag measurement.

Technique Drag Index

The technique drag index (TDI) was calculated as a measure of swimming efficiency (Kjendlie and Stallman, 2008):

$$TDI = \frac{D_A}{D_P} \qquad (2)$$

The TDI refers to the technique drag index (dimensionless), D_A refers to active drag or active drag coefficient (N or dimensionless, respectively), and D_P to passive drag or passive drag coefficient (N or dimensionless, respectively). This was done for the drag values in passive and active conditions and respective C_D's.

Thus, TDID refers to the TDI when absolute drag values are used, and TDI_{CD} refers to the TDI when the respective C_D is used.

Measurement of the Active Drag Coefficient (C_{DA})

The C_{DA} was calculated based on equation (1). Studies have shown that propulsion data can be used to replace drag data in such equation to calculate the C_{DA} (Havriluk, 2007; Morais et al., 2023). Propulsion was measured with wearable sensors (SmartPaddles®, Trainesense, Tampere, Finland) (Lopes et al., 2023). The sensors were attached to the swimmers' hands with silicon straps. Figure 2 depicts the sensor positioning.

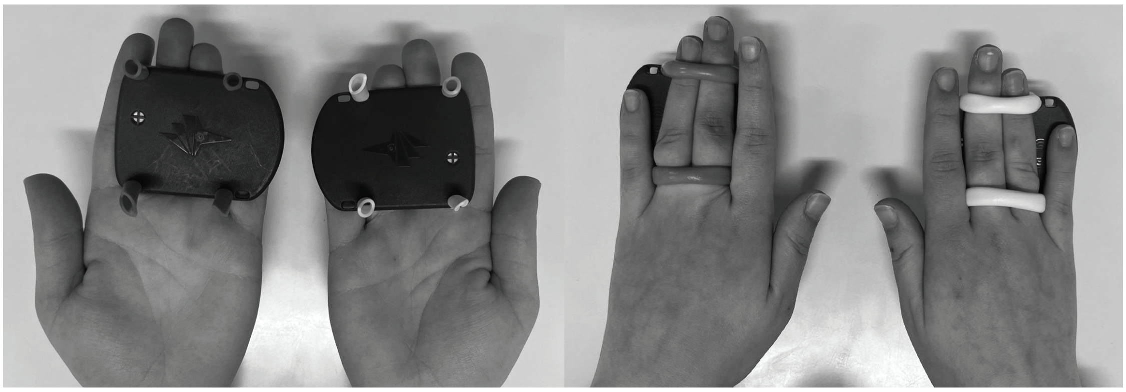

Figure 2. Positioning of the sensors.

The average propulsion of both upper limbs' arm-pulls performed between the 10th and 20th meter marks was retrieved from the database PoolShark Session Manager (https://sharksensors.com/). Afterwards, the total propulsion (P_{total}, in N) was calculated as the sum of the right and left arm-pulls. At the same time, the participants were attached to a speedometer string (SpeedRT, ApLab, Rome, Italy) to measure the swimming speed (in m/s). Afterwards, the speed-time series were imported into signal processing software (AcqKnowledge v. 3.9.0, Biopac Systems, Santa Barbara, USA). The signal was handled with Butterworth 4th order low-pass filter (cut-off: 5Hz). A video camera (GoPro Hero Black 7, USA) was placed in a fixed position in the mid-section of the swimming pool to record the swimmers in the sagittal plane and identify the hand entry. By doing this, it was possible to synchronize propulsion and speed data.

For the FSA measurement in active conditions, the participants were instructed to lie down on a bench in their swimsuits, with cap and goggles in the following positions: (i) right hand catch; (ii) right hand insweep; (iii) right hand exit and left hand catch; (iv) left hand insweep, and; (v) left hand exit and right hand catch (Lopes et al., 2023). Swimmers were photographed with a digital camera (Sony a6000, Tokyo, Japan) in the transverse plane (upward view) near a 2D calibration object. Then, each FSA position was measured by digital photogrammetry with dedicated software (Udruler, AVPSoft, USA). Afterwards, values at each position were interpolated using a cubic spline from which the FSA values were calculated at each 5% point of the stroke (Morais et al., 2020). The average value was used for further analysis.

Measurement of the Passive Drag (D_P) and Passive Drag Coefficient (C_{DP})

After knowing the swimmers' average swimming speed (i.e., during a maximal trial at front-crawl) between the 10th and 20th meter marks, the swimmers' D_P was measured at the same speed. For this purpose, the participants were attached via a nonelastic wire to a low-voltage isokinetic engine (Ben Hur, ApLAb, Rome, Italy) and were towed at a constant speed (Gatta et al., 2013). The participants were asked to (i) adopt a streamlined and hydrodynamic position, (ii) hold on to the wire, and; (iii) hold their breath after a maximal inspiration (Gatta et al., 2013). The lower limbs were passively lifted using a standard figure-eight-shaped pull-buoy (Golfinho, Portugal). As the software only allows the use of speeds every five hundredths (i.e., 1.00, 1.05, 1.10 m/s, etc), the swimmers' towing speed was set to the nearest value. Afterwards, data were handled with signal processing software as aforementioned. The average force between the 10th and 20th meter marks was used for analysis (Gatta et al., 2013; Zamparo et al., 2009). Afterwards, the C_{DP} was calculated based on equation (2). The FSA measurement for the C_{DP} calculation was done as previously described but with swimmers in an upright and hydrodynamic position. This position is characterized by the arms being fully extended above the head, one hand above the other, fingers also extended close together, and the head in a neutral position.

Statistical Analysis

The Shapiro-Wilk and the Levene tests were used to assess the normality and homoscedasticity, respectively. The mean plus one standard deviation (SD) and the relative difference (Δ, in %) were computed as descriptive statistics. The magnitude of the difference between C_D's was calculated with the paired samples t-test ($p<0.05$). Cohen's d estimated the standardized effect sizes, and deemed as: (i) trivial if $0\leq d<0.20$; (ii) small if $0.20\leq d<0.60$; (iii) moderate if $0.60\leq d<1.20$; (iv) large if $1.20\leq d<2.00$; (v) very large if $2.00\leq d<4.00$; (vi) nearly distinct if $d\geq4.00$ (Hopkins, 2019). Bland-Altman analysis included the plots of the difference and average of the C_{DA} against the C_{DP}, and the TDI_D against the TDI_{CD} (Bland and Altman, 1986). For qualitative assessment, it was considered that at least 80% of the plots were within the ±1.96 standard deviation of the difference (95% confidence intervals – 95CI).

Results

Table 1 presents the descriptive statistics of all variables measured. The FSA_{active} was 20.73±5.56% larger than $FSA_{passive}$, propulsion was 58.29±69.61% greater than drag, and C_{DA} was 24.60±46.55% greater than C_{DP}. The pairwise comparisons are presented in Table 2. The FSA_{active} was significantly larger with a large effect size than the FSApassive (mean difference= 0.0189, 95CI=0.0160 to 0.0218, d=1.88). The propulsion was also greater with a moderate effect size than drag for the same speed (mean difference= 14.48, 95CI=2.20 to 26.77, d=1.18). As for the C_D, the C_{DA} was significantly greater with a moderate effect size than the C_{DP} for the same speed (mean difference= 0.12, 95CI= -0.07 to 0.30, d=0.62). The TDI was significantly smaller but with a small effect size when measured with the C_D's values in comparison to drag (mean difference= -0.34, 95CI= -0.52 to -0.16, d=0.53) (Table 2).

Table 1. Descriptive statistics (mean ± standard deviation) of all variables measured with 95% confidence intervals (95CI). It also presents the relative difference between FSA's, propulsion and drag, and respective coefficients

	Mean	SD	95CI	Relative Difference [%]
Swimming speed [m/s]	1.25	0.14	1.15 to 1.35	
FSA_{active} [m^2]	0.098	0.009	0.092 to 0.105	20.73 ± 5.56
$FSA_{passive}$ [m^2]	0.079	0.012	0.071 to 0.088	
Propulsion [N]	52.48	9.78	45.48 to 59.48	58.29 ± 69.61
Passive drag [N]	37.99	14.38	27.71 to 48.28	
C_{DA} [dimensionless]	0.71	0.22	0.56 to 0.87	24.60 ± 46.55
C_{DP} [dimensionless]	0.60	0.12	0.51 to 0.68	
TDI_D [dimensionless]	1.58	0.73	1.06 to 2.11	19.69 ± 4.83
TDI_{CD} [dimensionless]	1.25	0.49	0.90 to 1.60	

Note: FSA_{active}: frontal surface area measure while swimming; $FSA_{passive}$: frontal surface area while towed; C_{DA}: active drag coefficient; C_{DP}: passive drag coefficient; TDI_D: technique drag index considering drag; TDI_{CD}: technique drag index considering the drag coefficient.

Table 2. Paired samples t-test comparison between variables related to the swimmers' hydrodynamics

	t-test (p-value)	MD	95CI	d [descriptor]
FSA_{active} vs $FSA_{passive}$ [m^2]	14.69 (<0.001)	0.019	0.016 to 0.022	1.88 [large]
Propulsion vs Drag [N]	2.67 (0.026)	14.48	2.20 to 26.77	1.18 [moderate]
C_{DA} vs C_{DP} [dimensionless]	1.42 (0.189)	0.12	-0.07 to 0.30	0.62 [moderate]
TDI_D vs TDI_{CD} [dimensionless]	-4.24 (0.002)	-0.34	-0.52 to -0.16	0.53 [small]

Note: FSA_{active}: frontal surface area measure while swimming; $FSA_{passive}$: frontal surface area while towed; C_{DA}: active drag coefficient; C_{DP}: passive drag coefficient; TDI_D: technique drag index considering drag; TDI_{CD}: technique drag index considering the drag coefficient. MD: mean difference; 95CI: 95% confidence intervals; d: Cohen's effect size.

Figure 3 depicts the Bland-Altman analysis of the C_{DA} against the C_{DP} (panel A), and the TDI_D against the TDI_{CD} at the same speed. In both cases, more than 80% of the plots were within the 95CI revealing a strong agreement between variables.

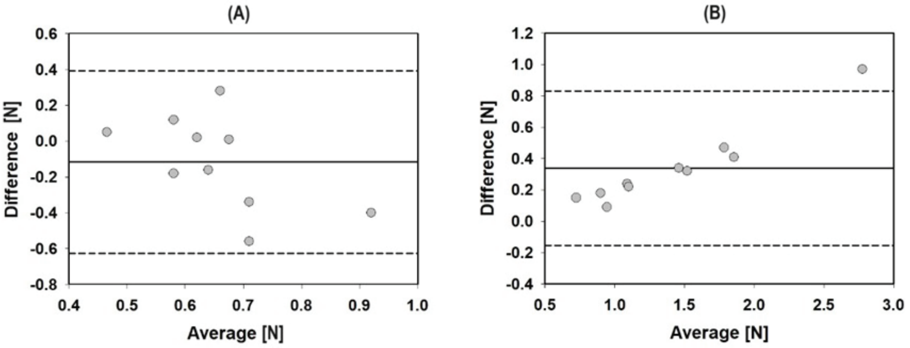

Figure 3. Bland Altman plots of the CD's (panel A) and the TDI (panel B). Dash lines refer to the 95% confidence intervals.

Discussion and Implications

The main aim of this study was to compare the C_{DP} with the C_{DA} at the same speed in the front-crawl stroke and understand the difference between using the TDI with drag (passive or active) and with their respective C_D's. The main findings were that proficient swimmers showed a larger C_{DA} in comparison to C_{DP}. Despite the non-significant differences noted, the effect size was moderate. The main reason for this could be the significant difference (with a large effect size) of the FSA noted in both conditions (larger in active than in passive). Also, the TDI calculated based on the C_D's revealed to be significantly smaller than with the drag values.

The methods used to determine C_D in both active and passive conditions are commonly reported in the literature (Gatta et al, 2016; Lopes et al., 2022; Vilas Boas et al., 2010). Regarding the active condition, the C_{DA} was calculated based on equation (1) in agreement with the fact that data related to propulsion can be used to replace the drag data in this equation to calculate the C_{DA} (Havriluk, 2007; Morais et al., 2023). The swimmers' C_{DP} was calculated based on the same equation where the drag value was obtained by a passive towing method (Cortesi et al., 2024; Scurati et al., 2019). This was done at the same speed as the speed measured while swimming during a maximal trial.

However, while the use of propulsion-related data to estimate the C_{DA} is supported in the literature (Havriluk, 2007; Morais et al., 2023), it is crucial to recognize the potential limitations and disputes concerning this approach. Specifically, the replacement of drag data with propulsion data in equation (1) may not fully capture the hydrodynamic differences between active and passive conditions. The C_{DA} is influenced by dynamic factors such as changes in body position and limb movement, which are not fully accounted for when using propulsion data alone. This could lead to discrepancies between the C_{DA} and C_{DP} that may not be solely attributable to differences in swimmer technique or body position, but rather to the inherent differences in the way these metrics are calculated. Furthermore, the passive towing method used to calculate the C_{DP} may oversimplify the drag experienced by a swimmer in a static position, failing to consider the complexities introduced by active swimming motions (Cortesi et al., 2024; Scurati et al., 2019). Therefore, while these methods are commonly used, they may introduce biases that need careful consideration when interpreting results.

Literature reports evidence about the methods used to measure drag (Havriluk, 2007). There are four methods to measure DA: (i) measurement of active drag (MAD); (ii) small perturbation method (SPM), also known as velocity perturbation method (VPM); (iii) assisted towing method (ATM), and; (iv) measurement of residual thrust (MRT) (Lopes et al., 2022). Overall, it was considered that despite there is no agreement among methods, they all measure the same phenomenon but in a different way (Lopes et al., 2022).

As aforementioned, the idea that the D_A is about 1.5 to 2.0 times larger than D_P seems to be consistent in the literature (Cortesi et al., 2024; Gatta et al., 2016; Narita et al., 2017). For instance, the authors plotted the DP and D_A values of six male competitive swimmers between 1.0 and 1.4 m/s for the active condition, and between 0.9 and 1.5 m/s for the passive condition (Narita et al., 2017). The authors noted that for similar speeds, the D_A tended to be greater in D_A in comparison to D_P, and this difference increased with speed (Narita et al., 2017). On the other hand, it was claimed that most research on swimming does not report the C_D's, particularly in active conditions (Morais et al., 2023). Additionally, and as far as our understanding goes, there is no information about the comparison of the respective C_D's at the same speed. Our results revealed that the C_{DA} was greater (non-significant) than the C_{DP} but with a strong agreement. One can argue that the main reason for this difference was the FSA. In passive drag, the swimmers are measured in a streamlined position without movement of the propulsive segments. While in active conditions, the motion of the propulsive segments plays a key role. Indeed, it was shown how FSA changes during the stroke cycle and its implications on drag (Gatta et al., 2015; Morais et al., 2020). It seems that this FSA change in active conditions also presents implications on the C_{DA} but with a smaller magnitude than in drag.

Regarding the TDI, our results related to the TDID are within the literature thresholds (D_A was, on average, 1.58 times larger than D_P). On the other hand, based on the respective C_D's, the C_{DA} was on average, 1.25 times larger than C_{DP}. In a study about this topic, the authors reported a TDI value of 1.15 for adult competitive swimmers (Kjendlie and Stallman, 2008). However, the D_A and C_{DA} were measured at maximal speeds and the D_P and C_{DP} were measure at maximal speeds but based on the gliding speed decay. Therefore, one can argue that some differences in speed could be noted. In our study, we calculated both TDI's (drag and C_D's) at the same speed to understand the difference. The significant difference verified in our study between these two TDI's (i.e., based on drag or its respective C_D) may also indicate that the TDI is overestimated when measured with drag rather than with the C_D. This comparison is of particular interest because the C_D is the parameter that better represents the swimmer's hydrodynamic profile (Havriluk, 2007; Morais et al., 2024; Zamparo et al., 2009). Therefore, one can argue that it is also important to compare the C_{DA} against the C_{DP} at the same speed to get deeper insights into the swimmers' hydrodynamics, which ultimately will affect performance.

Although there are no gold standard methods for measuring propulsion, drag, and respective C_D's, those used in the present study are a simple and feasible way to measure these data. Coaches should be aware that the C_D is a "constant" parameter independent of speed and is mainly related to the dimensions of the body (i.e., volume, FSA, etc.) and the shape of the body adopted when moving (i.e., technique), as well as viscosity and the density of water. In this context, by being able to analyze C_D in active and passive situations to compare them without dismissing each one as unnecessary, coaches will obtain much more real data. Consequently, this will allow them to understand whether their swimmers' technique is adequate. Therefore, the interpretation of the effects of C_D's and not just drag, whether passive or active, must be decisive for training guidance, also based on the interpretation of the TDI. As main limitations, it can be considered: (i) the small sample size where only collegiate swimmers were evaluated (despite being proficient swimmers), and; (ii) this comparison was only done at maximal swim speeds. Therefore, future studies should recruit more swimmers of different competitive levels and age groups and at different swim speeds to gather deeper insights about this topic.

Conclusions

This study concludes that proficient swimmers exhibited a higher C_{DA} compared to C_{DP}, with a moderate effect size observed despite the non-significant differences. This discrepancy may be primarily attributed to the significant difference (with a large effect size) in the FSA noted between the active and passive conditions, where FSA was larger in active conditions. Additionally, the TDI, when calculated using the respective C_D's values, was found to be significantly lower compared to the values derived from absolute drag measurements, suggesting that TDI as an indicator of swimming efficiency may be overestimated when based on absolute drag rather than on C_D's.

Acknowledgments

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