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Measurement of the active drag coefficient in front-crawl: A stroke-by-stroke analysis

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ABSTRACT

The purpose of this study was to understand the change in active drag coefficient (C_{DA}) over successive stroke cycles in front-crawl and the relationship between swimming speed and C_{DA}. Eighteen national competitive swimmers (nine girls and nine boys with a mean age of 14.91 ± 0.59 years) were recruited. Swimming speed, propulsion (F_{total}) and frontal surface area were measured to calculate the C_{DA}. Swimming speed ($F = 1.790$, $p = 0.182$, $\eta^2 = 0.07$) and C_{DA} ($F = 0.907$, $p = 0.413$, $\eta^2 = 0.06$) did not change significantly over time, but swimming speed showed a decrease between the second and third stroke cycle. On the other hand, the F_{total} changed significantly over time ($F = 4.437$, $p = 0.019$, $\eta^2 = 0.21$). Swimming speed and C_{DA} showed a linear and strong relationship ($R^2 = 63.8$ %). A stroke-by-stroke analysis showed that national level swimmers were able to maintain their hydrodynamic profile during a front-crawl maximal trial. Thus, it can be argued that a decrease in swimming speed can be related to a decrease in F_{total}. Swimming speed and C_{DA} showed an inverse and significant relationship, with lower values of C_{DA} resulting in faster swimming speeds.

1. Introduction

Swimming is a time-based sport that is highly dependent on the net balance between propulsion and drag (Toussaint and Beek, 1992). Propulsion refers to the ability of swimmers to generate in-water force to propel themselves forward and drag against water resistance (Toussaint, 2011). Thus, hydrodynamics is one of the most studied topics among swimming researchers (Barbosa et al., 2015; Narita et al., 2017).

Regarding drag, this can be calculated based on Newton's equation:

$$D = \frac{1}{2} \bullet v^2 \bullet \rho \bullet S \bullet C_D \quad (1)$$

In which D is the drag force (N), ρ is the density of water (kg/m^3), v is the swimming speed (m/s), S is the projected frontal surface area (FSA) of the swimmer (m^2) and C_D is the coefficient of drag (changing according to shape, orientation, and Reynolds number). Drag is composed by three components: (i) friction drag (depends on the friction between the skin and the water); (ii) pressure drag (depends on body surface area), and; (iii) wave drag (depends on the water surface deformation) (Toussaint and Beek, 1992). In the specific case of the aquatic environment, there is also an inertial component (called "added mass of water") associated to the variation in speed (Caspersen et al., 2010). A body immersed in water behaves as it was heavier, and thus, additional mechanical work is required against both the inertia of the body and that of the displaced fluid (Lauer et al., 2015; Zamparo et al., 2020).

Recently, it has been reported that the drag coefficient (C_D) (passive – C_{DP}, or active – C_{DA}) should be used to understand the hydrodynamic profile of swimmers (Morais et al., 2023). This (i.e., hydrodynamic profile) is considered to be less dependent on swimming speed and is strongly related to the swimmer's shape (i.e., morphology), orientation, and Reynolds number, as well as the swimmer's coordination (Lopes et al., 2022; Toussaint and Beek, 1992). When measuring C_{DA} during swimming, researchers often use the average data from one swim trial (Gonjo and Olstad, 2022; Silva et al., 2019). However, swimming speed tends to decrease over time during maximal trials (Morais et al., 2020a; Morouco et al., 2017). It has been found that sprinting swimmers tend to increase their intra-cyclic variation in resultant horizontal force (i.e., propulsion fluctuation) over time, which leads to greater speed fluctuations and thus poorer performance (Morouco et al., 2017). Nevertheless, it can be argued that such a decrease in speed could be related not

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only to propulsion parameters, but also to changes in the swimmers' C_{DA}. However, to the best of our knowledge, there is no evidence in the literature regarding the change in C_{DA} in a stroke-by-stroke analysis in front-crawl. This information can provide new insights into the swimmer's ability (or inability) to maintain a good hydrodynamic profile while swimming.

Therefore, the objectives of this study were to understand the change in C_{DA} over successive stroke cycles in front-crawl and the relationship between swimming speed and C_{DA}. It was hypothesized that the C_{DA} would increase over time (i.e., decreases in speed would lead to increases in C_{DA}). There would also be an inverse relationship between swimming speed and C_{DA} (the lowest C_{DA}s would be associated with the fastest speeds).

2. Methods

The sample consisted of 18 competitive swimmers (nine girls and nine boys) who regularly participated in regional and national competitions and in a talent identification program (Tier 3) (McKay et al., 2021). The demographics of the swimmers are shown in Table 1. To be included in the study, swimmers had to be uninjured and training regularly for the six months prior to data collection. All procedures were in accordance with the Declaration of Helsinki regarding human research, and the Polytechnic Ethics Board approved the research (N. 72/2022).

2.1. Frontal surface area data collection

For FSA measurements, swimmers were photographed with a digital camera (Sony a6000, Tokyo, Japan) in the transverse plane near a 2D calibration (Morais et al., 2020b). Swimmers change their FSA during swimming. Such a change is thought to have a direct effect on the hydrodynamics of the swimmers (Morais et al., 2020b). To gain insight into this change, swimmers were instructed to lie down on a bench wearing their swimsuit, cap, and goggles. Swimmers were photographed at the five key moments of the stroke cycle: (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 (Morais et al., 2020b). This was done to represent the duration of a full stroke cycle. The lower trunk was supported on the bench so that the swimmers could move their upper trunk more freely. The beginning and end of each stroke cycle were considered to be the consecutive entry of the right hand into the water. Each FSA position was then measured using digital photogrammetry with a dedicated software (Udruler, AVPSoft, USA). The values at each position were interpolated using a cubic spline, from which the FSA values at each percentage point (each 5 %) of the stroke cycle were calculated (Fig. 1 – panels A). The average FSA (m^2) of the five key moments was then used for the C_{DA} calculation.

2.2. In-water research design

After a standardized 1,000-m warm-up, swimmers performed three 25-m trials with a push-off start and the fastest was used for analysis. The swimmers were analyzed for three consecutive stroke cycles between the 10th and 20th meters. Swimmers were instructed to perform non-breathing swim strokes during this distance to avoid changes in coordination or technique (McCabe et al., 2015).

2.3. Swimming speed data collection

To measure swimming speed, the string of a mechanical device (SpeedRT, ApLab, Rome, Italy) was attached to the waist of the swimmers (f = 100 Hz). The speed-time series were then imported into a 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: 5 Hz) after residual analysis. A video camera (Hero 7, GoPro Inc., San Mateo, CA, USA) synchronized with the mechanical device filmed the swimmers in the sagittal plane to identify the entry and exit of the hand into the water. Swimming speed (m/s) was obtained from the software during three consecutive stroke cycles (based on hand entry and exit).

2.4. Propulsion data collection

Propulsion data was collected simultaneously with swimming speed. A pressure sensor system ($f = 100$ Hz) (Swimming Technology Research, USA) was used for this purpose. This system is based on sensors that estimate the in-water pressure and has been shown to be a reliable setup for obtaining peak and mean hand resultant force in young competitive swimmers (Santos et al., 2022). They also presented non-significant differences with a strong agreement with another pressure system that also included Inertial Measurement Units and calculates the propulsive force generated (Marinho et al., 2022). The sensors were placed between the third and fourth metacarpals to measure the pressure differential between the palmar and dorsal surfaces (Morais et al., 2020a). The hand is considered to be the best proxy for the point of application of the propulsion vector (Gourgoulis et al., 2013) and the anatomical body part responsible for the force application on water generated by the entire upper limb (Bilinauskaite et al., 2013). The time-force series were then imported into the same signal processing software and the signals were processed as described above. Each arm-pull was defined as the time spent between the entry and exit of the hand into the water. Mean propulsion was calculated for the right upper limb (F_{right}, N) and left upper limb (F_{left}, N) arm-pulls. Then, the total propulsion generated by the full stroke cycle (F_{total}, N) was calculated as the sum of F_{right} and F_{left}. Finally, the C_{DA} in each stroke cycle was calculated as:

$$C_{DA} = \frac{2 \bullet F_{total}}{\rho \bullet v^2 \bullet FSA} \tag{2}$$

where C_{DA} is the active drag coefficient (dimensionless), F_{total} is the total propulsion generated over the stroke cycle (N), ρ is the density of the water (as 997 kg/m^3), v is the swimming speed (m/s), and FSA is the swimmer's average frontal surface area (m^2) considering the five key moments of the stroke cycle. This was done as reported by Havriluk (2007).

2.5. Statistical analysis

The mean plus one standard deviation (SD) was calculated as descriptive statistics. The coefficient of variation (CV, %) was used to understand the magnitude of variation in the FSA across the five key moments. One-way repeated measures ANOVA was used to verify the within-subject effect. The effect size index (eta square – η^2) was computed and interpreted as: (i) no effect if $0 < \eta^2 \leq 0.04$; (ii) minimum if $0.04 < \eta^2 \leq 0.25$; (iii) moderate if $0.25 < \eta^2 \leq 0.64$ and; (iv) strong if $\eta^2 > 0.64$ (Ferguson, 2009). When appropriate, Bonferroni post-hoc correction was used to test for pairwise differences ($p < 0.017$) and Cohen's d was used to estimate the standardized effect sizes (Hopkins, 2002). Simple linear regression was used to understand the relationship between swimming speed and C_{DA}. As a rule of thumb and for qualitative interpretation, the relationship was defined as follows: very weak if $R^2 < 0.04$, weak if $0.04 \leq R^2 < 0.16$, moderate if $0.16 \leq R^2 < 0.49$, high if $0.49 \leq R^2 < 0.81$, and very high if $0.81 \leq R^2 < 1.0$.

3. Results

Table 1 shows the descriptive statistics of all measured variables. The FSA varied across the five key moments with the largest area in key moments two (right hand insweep) and four (left hand insweep). Over the five key moments, the FSA showed a CV of 17.52 ± 1.93 %. Swimming speed indicated a maintenance between the first and second stroke

Table 1
Descriptive statistics (mean ± standard deviation – SD) of all variables measured. For the frontal surface area (FSA) the value in each key-moment is presented, as well as the average of the five and the respective coefficient of variation (CV). For the swimming speed, propulsion (F_{total}), and active drag coefficient (C_{DA}) the descriptive data in each stroke cycle are presented as well as the data for the repeated-measures ANOVA one-way.

	Mean ± SD Girls	Boys	Overall
Age [years]	14.40 ± 0.23	15.41 ± 0.33	14.91 ± 0.59
Body mass [kg]	54.31 ± 4.58	66.93 ± 8.63	60.62 ± 9.34
Height [cm]	160.11 ± 4.91	176.11 ± 6.83	168.11 ± 10.05
Arm span [cm]	165.44 ± 5.94	182.22 ± 8.15	173.83 ± 11.06
WAPS 100 m freestyle [a.u.]	479.00 ± 78.68	483.78 ± 69.27	481.39 ± 71.95

	Mean ± SD					
	1st key-moment	2nd key-moment	3rd key-moment	4th key-moment	5th key-moment	CV
FSA [m^2]	0.0872 ± 0.0124	0.1429 ± 0.0203	0.0878 ± 0.0135	0.1413 ± 0.0218	0.0872 ± 0.0124	17.52 ± 1.93

	Mean ± SD				
	1st stroke cycle	2nd stroke cycle	3rd stroke cycle	F-ratio (p)	η^2
Speed [m/s]	1.52 ± 0.13	1.52 ± 0.13	1.50 ± 0.13	1.790 (0.182)	0.07
F_{total} [N]	70.88 ± 9.35	70.75 ± 9.56	67.35 ± 10.05	4.437 (0.019)	0.21
C_{DA} [dimensionless]	0.53 ± 0.12	0.54 ± 0.14	0.53 ± 0.13	0.907 (0.413)	0.06

WAPS – World Aquatic Point Scoring; FSA – frontal surface area; F_{total} – total propulsion; C_{DA} – active drag coefficient; η^2 – eta squared (effect size index).

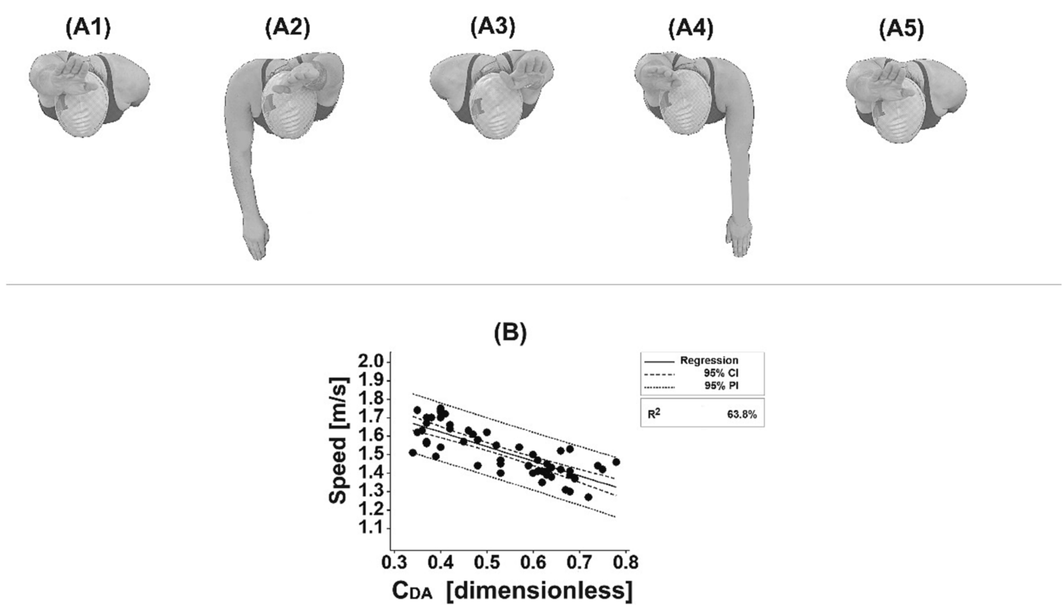

Fig. 1. Top panels (prefix A) – Illustration of the five key-moments of a full stroke cycle: (A1) – right upper-limb catch; (A2) – right upper-limb insweep; (A3) – right upper-limb exit and left upper-limb catch; (A4) – left upper-limb insweep, and; (A5) – left upper-limb exit and right upper-limb catch. Bottom panel (B) – relationship between swimming speed and C_{DA} (active drag coefficient). 95CI – 95 % confidence intervals; 95PI – 95 % prediction intervals; R^2 – coefficient of determination.

cycle and decreased in the third stroke cycle, but without a significant effect ($F = 1.790$, $p = 0.182$, $\eta^2 = 0.07$) (Table 1). The F_{total} presented a similar trend, but the decrease was more pronounced in the third stroke cycle, resulting in a significant effect with a minimum effect size ($F = 4.437$, $p = 0.019$, $\eta^2 = 0.21$) (Table 1). However, Bonferroni correction did not reveal any significant differences between pairwise comparisons ($p < 0.017$). As for the C_{DA}, an overall maintenance was observed over the three stroke cycles without a significant effect ($F = 0.907$, $p = 0.413$, $\eta^2 = 0.06$) (Table 1). Fig. 1 shows the relationship between swimming speed and C_{DA} (panel B). Swimming speed presented a linear and large relationship with C_{DA} ($R^2 = 63.8$ %).

4. Discussion

The objectives of this study were to understand the change in C_{DA} over successive stroke cycles in front-crawl and the relationship between swimming speed and C_{DA}. The main findings indicate that both swimming speed and C_{DA} did not change significantly over time. However, swimming speed tended to decrease from the second to the third stroke cycle (but not significantly). On the other hand, F_{total} changed significantly with a decrease especially between the second and third stroke cycle (but not significantly). Swimming speed presented a linear and large relationship with C_{DA}.

The data from this study showed that swimmers tended to decrease their swimming speed (not significantly) and F_{total} (significantly) over successive stroke cycles. Indeed, it has been shown experimentally that swimmers tend to decrease their swimming speed during maximal trials and that this decrease is strongly related to a decrease in propulsion (Morais et al., 2020a). This analysis also considered consecutive stroke cycles rather than the average of the entire trial. On the other hand, studies on C_{DA} usually report to values related to the average of a given trial (Marinho et al., 2010; Silva et al., 2019). As a result, researchers and coaches are unable to fully understand whether water resistance can also affect the rate of deceleration during successive strokes. This means that it is not possible to establish a direct relationship stroke-by-stroke, and researchers and coaches can only get an overall perspective of the entire trial. In a study on swimming drag, it was argued that the instantaneous value of the dimensionless coefficient of the frontal component of the active drag force (i.e., the drag coefficient) is the main reason for the existing differences in maximum swimming speeds between the four different swimming strokes (Kolmogorov et al., 2021). This highlights the importance of studying the C_{DA} to understand the hydrodynamic profile of swimmers.

Biomechanically, swimmers can increase their swimming speed by increasing propulsion or minimizing drag (or both together) (Toussaint and Beek, 1992). Therefore, if a swimmer shows an increase in swimming speed with an unchanged increase in propulsion, this change suggests that he/she has primarily improved his/her hydrodynamic profile. The current data indicate that the recruited swimmers (national level) were able to maintain their C_{DA} over the measured stroke cycles. This may occur because they have a consolidated stroke mechanics that allows them to minimize resistance by maintaining good alignment between the longitudinal axis of the body and the intended line of progression (Papic et al., 2020; Yanai, 2004). This good alignment can also minimize the variation in the frontal surface area. That is, swimmers maintain an alignment that does not significantly increase their frontal surface area, which would lead to an increase in resistance. Thus, from a biomechanical point of view, since a decrease in swimming speed was observed (although not significant), it can be said that such a decrease occurred based on a significant decrease in the F_{total} (other physiological variables may also be related but are not considered here). It should also be noted that only the upper limb propulsion was considered in the present study. Swimming speed is achieved by the propulsion generated by the upper and lower limbs (Toussaint and Beek, 1992). However, studies on this topic have reported that upper limb arm-pulls account for 90 % of the total propulsion (Deschodt et al., 1999) and 88 % of total swimming speed (Bartolomeu et al., 2018) during maximal trials. Furthermore, studies tend to estimate the FSA (Narita et al., 2018) or measure it as being the largest area in the streamlined position (Vilas-Boas et al., 2010). Consequently, they do not consider the change in FSA during the stroke cycle. It appears that this leads to an underestimation of the FSA observed during the swim stroke (Morais et al., 2020b); and ultimately to misleading results and interpretation of the C_{DA} measurement.

C_{DA} explained 63.8 % of the variance in swimming speed, with higher C_{DA} values resulting in slower swimming speeds. This means that the fastest swimmers were able to reduce water resistance more and therefore achieve the fastest swimming speeds. In fact, C_{DA} was shown to be significantly and negatively correlated with swimming speed (i.e., lower C_{DA} resulted in faster speeds) (Wettengl et al., 2023). In addition, comparisons between skill levels (Silva et al., 2019) and age groups (Wettengl et al., 2023) showed that the best skilled swimmers (fastest speeds) or oldest swimmers (fastest speeds) also had lower C_{DA}s compared to their worst or younger counterparts. The C_D, although passive or active, has the great advantage of being less sensitive to the swimming speed. Therefore, as in other speed-dependent sports (cycling or skiing), the C_D should be used as a key indicator of the swimmers' hydrodynamic profile.

The main limitations of this study are that: (i) only the propulsion generated by the upper limbs was measured, and; (ii) the FSA was measured on land, simulating the five key moments of the front-crawl stroke cycle. Regarding the former, it can be argued that lower limb propulsion can also contribute significantly to swimming speed. Therefore, future studies should include it. Regarding the FSA, there are more specific techniques to measure it under active conditions, i.e., during swimming (González-Ravé et al., 2022; Morais et al., 2020b), however, it should be noted that these techniques are more time-consuming and complex. Future studies should focus on measuring the change in C_{DA} at different speeds and in all four swim strokes. More knowledge is needed to better understand if the C_{DA} measurement based on the average of a given trial is sufficient to provide insight into the hydrodynamic profile of swimmers, or if a stroke-by-stroke analysis provides more information. That is (i) to analyze strokes at the beginning, middle, and end of the swimming pool to evaluate a hypothetical fatigue effect on the drag-speed relationship, and; (ii) perform a within-subject analysis to get deeper insights about how the C_{DA} might change in the same swimmer. Other variables such as the index of coordination (which gives an individual insight into the swimmer's coordination) could also be included to understand if the swimmer's stroke technique has some influence on the C_{DA}. That is, the swimmers' motor adaptations can be different due to both intra-cycle and inter-individual variability. Therefore, both assumptions can help coaches and biomechanics analysts to get new insights about the importance of the C_{DA} on the performance improvement.

5. Conclusions

It as was possible to calculate the C_{DA} in a stroke-by-stroke analysis. At least for national level swimmers, the C_{DA} did not change significantly over time. The tendency for swimming speed to decrease may be related to the decrease in propulsion and not to the increase in C_{DA}. C_{DA} showed an inverse and linear relationship with swimming speed. The lowest C_{DA}s were associated with the fastest swimming speeds. Researchers and coaches should be aware that swimmers with good performance levels may be able to maintain their hydrodynamic profile over time during front-crawl maximal trials.

CRediT authorship contribution statement

Jorge E. Morais: Conceptualization, Methodology, Data curation, Writing - original draft, Writing - review & editing. **Daniel A. Marinho:** Conceptualization, Methodology, Data curation, Writing - original draft, Writing - review & editing. **Tiago M. Barbosa:** Conceptualization, Methodology, Data curation, Writing - original draft, Writing - review & editing.

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.

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