Journal of Biomechanics 177 (2024) 112390

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech

Exploring the impact of breathing patterns on active drag in breaststroke swimming

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ARTICLE INFO

Keywords:
Hydrodynamics
Swimming
Performance
Biomechanics

ABSTRACT

This study aimed to compare active drag (D_a), coefficient of hydrodynamic force (C_{Da}) and, total external mechanical power (P_{tot}) between two breathing patterns in breaststroke: breathing every stroke versus every two strokes. A 6-week intervention program was conducted. Fifteen swimmers carried out two all-out bouts of 25 m using the velocity perturbation method in each breathing pattern. The study analyzed the swimmers' velocity (swimming freely and with the towed body), D_a, C_{Da} and P_{tot}. Individual data analysis revealed that 40 % of the sample experienced a decrease in D_a when breathing every two strokes, with some achieving higher velocities. Conversely, nine swimmers exhibited lower D_a values while breathing every stroke, with six of them also showing higher velocity values compared to breathing every two strokes. When comparing the pooled sample using paired t-tests, no differences were found in D_a, C_{Da} and, P_{tot} between the two breathing patterns. Furthermore, using ANCOVA analysis, results indicated that neither sex nor swimming velocity influenced the variables studied.

1. Introduction

Swimming performance is affected by both the propulsive and resistive forces (Pendergast et al., 2005). Hydrodynamic drag (D) is the external force acting on the swimmer's body, opposing their movement (Toussaint et al., 1988, 2004), and manifests in two forms: passive and active drag (D_a) (Pendergast et al., 2005). The latter, is the force opposite to displacement that swimmers have to overcome while attempting to maintain their movement through the water. The intensity of D can be calculated based on Newtonian fluid equation:

$$D = \frac{1}{2} C_D \rho v^2 S \tag{1}$$

where C_D is the drag coefficient, ρ is the density of the fluid, v represents the velocity of the swimmer, and S indicates the maximum cross-sectional area of the body transverse to the direction of the force.

One method to estimate D_a force is the Velocity Perturbation Method (VPM) (Kolmogorov & Duplishcheva, 1992), which assumes that the swimmer can deliver constant useful mechanical power output, as verified by Kolmogorov (2023). VPM allows swimmers to swim freely, representing their swimming technique during competition and velocity. It is notable for its non-intrusive approach and suitability for assessing swimmers. Many studies have used VPM to measure swimmers' hydrodynamics (Marinho et al., 2010; Morais et al., 2014), showing its reliability in measuring D_a (Toussaint et al., 2004).

D_a can be influenced by variations in the body's shape, particularly frontal surface area, and movement of the body segments, which contribute to inefficient swimming techniques (Morais et al., 2020; Sacilotto et al., 2023; Zamparo et al., 2009). Kolmogorov et al. (1997) obtained a smaller D_a coefficient for elite swimmers than for their sub-elite counterparts in some swimming techniques, such as female breaststroke, male butterfly stroke, and front crawl, likely due to superior technical proficiency. Therefore, swimming fast could be impacted by the athlete's body shape and dimensions as well as by the ability to produce propulsion and reduce D_a through proficient stroke technique (Sacilotto et al., 2023).

Among the various swimming techniques, studies have noted that breaststroke tends to have higher values of frontal area and

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https://doi.org/10.1016/j.jbiomech.2024.112390
Accepted 24 October 2024

D_a(Kolmogorov & Duplishcheva, 1992; Kolmogorov et al., 1997, 2021). In this technique, swimmers take a breath during each stroke cycle as a mainstream procedure. However, this practice requires lifting the head and a portion of the upper body significantly above the water, leading to an increase in frontal surface area and, consequently, D (Clarys, 1975). According to the *World Aquatics* 2017–2021 rules, it is mandatory to ensure that some part of the head breaks the water surface during each complete cycle of the breaststroke technique. The wording of the rule means that swimmers do not need to fully lift their heads and torsos every stroke for breathing; rather, they must ensure their heads breaks the water's surface, even if they keep the face in the water and do not breath. By reducing the frequency of breaths, swimmers can maintain a more streamlined position in the water, thereby minimizing frontal drag and conserving energy. This adjustment can potentially enhance efficiency and overall performance during the race. These are the same arguments used for years to support choosing the butterfly technique with one breathing cycle for each two swimming cycles.

In fact, a reduced breathing technique is often used, mostly in the butterfly and front crawl technique, to keep a high velocity while staying in a more streamline position, and therefore reducing drag. In the front crawl, breath-holding led to faster 25 m time-trials compared to higher breathing frequencies (Couto et al., 2015; Pedersen & Kjendlie, 2006). In the butterfly technique, trunk inclination significantly increased during inhalation compared to breath-holding (Hahn and Krug, 1992; Alves et al. 1999).

These findings underline the importance of considering breathing patterns in swimming to enhance performance, notably in breaststroke due to the rules constraints. Consequently, the aim of this study was to compare active drag, coefficient of hydrodynamic force and, total external mechanical power between two breathing patterns in the breaststroke technique: inhaling every stroke versus every two strokes. It was hypothesized that breathing every two strokes would result in lower active drag compared to breathing every stroke.

2. Methods

2.1. Participants

Fifteen swimmers from local swimming teams took part in the study. Their demographic characteristics are presented in Table 1. Inclusion criteria encompassed that, swimmers would need to have at least four years of competitive background in the sport and achieve a performance level exceeding 250 points according to FINA standards in the 100 m breaststroke. The swimmers participated in regular training sessions between 6 and 8 times a week, each lasting from one and a half to two hours. Swimmers received thorough briefing on procedures, risks, and benefits, and provided written consent. For underage participants, consent was obtained from parents or legal guardians. Approval for all experimental procedures was granted by the local research ethics committee (CEFADE 36 2022). The protocol followed the rules of the Declaration of Helsinki (2000).

Table 1
Individual data of the participants.

Subjects	Age (years)	Body mass (kg)	Height (cm)	FINA Points (100 m breaststroke)
F1	12.1	37.0	151.0	259
M1	20.4	70.0	180.0	518
F2	20.4	61.0	170.0	464
M2	13.7	54.0	165.0	295
F3	12.6	49.0	154.0	280
F4	26.1	58.0	169.0	480
M3	15.1	56.0	173.0	378
M4	19.6	74.0	182.0	559
F5	17.2	54.0	162.0	455
F6	13.0	30.0	145.0	250
F7	12.4	54.0	166.0	296
F8	25.1	59.0	166.0	259
M5	11.6	43.0	147.0	257
F9	14.0	43.0	163.0	455
M6	12.3	45.0	153.0	250
Mean ± SD	16.4 ± 4.8	52.5 ± 11.7	163.1 ± 11.2	363.7 ± 112.7

2.2. Intervention program

A 6-week intervention program comprising of 18 sessions (3 sessions/week, 20 min each) was conducted in a 25 m indoor pool, with the goal of familiarization with the new breathing pattern. During the first week, swimmers were briefed on the new breathing pattern by watching video clips and concurrent cues by the coach. Thereafter, were allowed to self-explore this technique in the water. Then, the coach's feedback progressively increased from analytical to a more global intervention. In the following two weeks, swimmers underwent three sessions with low intensity and increasing volume. In the 4th and 5th weeks, an increase in intensity was implemented. The last week alternated between volume and intensity. During the practice sessions, subjects received specific coaching feedback on technical points. Subjects were assigned to train under this program to progressively increase the practice difficulty, with appropriate challenges beyond their skill levels, to facilitate skill learning (Guadagnoli & Lee, 2004).

2.3. Data collection

After the intervention program, swimmers were evaluated. They carried out two all-out bouts of 25 m using the VPM in each breathing pattern, which were randomized. The key assumption to calculate D_a by VPM is that equal power output is achieved with and without a perturbation device attached to the swimmer (Kolmogorov & Duplishcheva, 1992), which was verified by Kolmogorov (2023) for specifically trained swimmers. The swimmer performs two maximal effort trials, one with a known additional resistance and one without. As the maximal power output should be equal in both conditions, the observed difference in velocity should be due to the effect of the added resistance. Subjects performed at least one practice trial to become familiar with the nature of the experiment and were given four minutes rest between each trial to eliminate the influence of fatigue on their performance (Toubekis et al., 2011).

Swimming velocity was assessed over 13 m (between 11th m and 24th m from the starting wall), using a manual stopwatch by two expert evaluators to measure the time spent to cover this distance (ICC = 0.88). The mean value was used for further analyses. During the trial, the swimmer swam alone (to reduce drafting and pacing effects), with a push-off start and was instructed to undergo an all-out swim and to not do an underwater pull–out. The VPM mean D_a is calculated using the following equation (Kolmogorov & Duplishcheva, 1992):

$$D_a = \frac{D_b \times v_b \times v^2}{v^3 - {v_b}^3} \tag{2}$$

where, D_a represents the swimmer's active drag at maximal velocity, D_b is the resistance of the perturbation buoy, and v_b and v are the swimming velocities with and without the perturbation device, respectively. The total external mechanical power (P_{tot}) was determined as (Kolmogorov & Duplischeva, 1992):

$$P_{tot} = D_a \times v \tag{3}$$

The drag of the perturbation buoy was calculated from the manufacturer's calibration of the buoy drag characteristics and its velocity (Kolmogorov & Duplischeva, 1992). The active drag coefficient (C_{Da}) was calculated as:

$$C_{Da} = \frac{2 \times D_a}{\rho \times S \times v^2} \tag{4}$$

where ρ is the density of the water (assumed to be 1000 kg/m^3), D_a is the swimmer's active drag, v is the swimmer's velocity and S is the projected frontal surface area of the swimmers. S was estimated as Kolmogorov & Duplishcheva (1992) and Kolmogorov et al. (1997), where S is the characteristic body size equal to the volume of the subject's body raised to the power of 2/3 (m^2). Hence, dependent variables included the swimmer's velocity (swimming freely and with the towed body – v_{free} and v_{tow}, respectively), active drag (D_a), coefficient of hydrodynamic force (C_{Da}) and, total external mechanical power (P_{tot}).

2.4. Statistics

Data was analyzed on SPSS Version 25.0 for Windows (SPSS Inc., Chicago, IL, USA) and Microsoft Excel. All the selected variables were checked for normality with the Shapiro–Wilk test. Mean and standard deviations for all variables were calculated, including 95 % interval confidence. The statistical significance was set at $p \leq 0.05$. The paired samples *t*-test was used to compare variables between the two breathing patterns. Cohen's d was also computed. Effect sizes were considered as small ($d = 0.2$), moderate ($d = 0.5$), and large ($d = 0.8$). ANCOVA analysis was conducted to examine the difference in dependent variables between the two breathing patterns, while controlling for the covariate age and swimming velocity (freely). Prior to conducting ANCOVA, tests for homogeneity of variance (Levene's Test) and normality (Shapiro-Wilk Test) were conducted to check assumptions. No significant violations of these assumptions were found ($p > 0.05$). Effect size was computed based on eta-squared (η^2) and interpreted as: without effect if $0 < \eta^2 < 0.04$; minimum if $0.04 < \eta^2 < 0.25$; moderate if $0.25 < \eta^2 < 0.64$ and; strong if $\eta^2 > 0.64$.

3. Results

Table 2 shows that, out of the 15 swimmers examined, six (F3, F5, F9, M3, M4, and M6), accounting for 40 % of the total sample, showed a lower *Da* while swimming Br 1/2 compared to Br 1/1. The largest difference observed was approximately 85 N (F9). Notably, four of these swimmers (F5, F9, M3, and M6) also exhibited faster velocity swimming Br 1/2. Conversely, nine swimmers (60 %) exhibited higher D_a values swimming Br 1/1 (F1, M1, F2, M2, F4, F6, F7, F8, and M5), with the wider difference being 52 N and 50 N (M5 and F6, respectively) when comparing the two breathing patterns. Among these swimmers, six also demonstrated increased velocity while swimming Br 1/1 (with differences ranging from 0.01 to 0.05 m.s^{-1}). Remarkably, three swimmers (M1, F4, and F6) displayed higher D_a values while swimming Br 1/2, yet they achieved higher velocity with this pattern compared to swimming Br 1/1.

A paired samples *t*-test was used to compare swimmer's hydrodynamic characteristics between the two breathing patterns (Table 3). Notably, our analysis revealed no significant differences in these variables between the two breathing patterns ($p > 0.05$). However, Cohen's d effect size estimates ranged from small to moderate ($0.057 \leq d \leq 0.516$) across all variables studied. To examine the effect of age and velocity as potential confounding and interacting factors, ANCOVA analysis was computed (Table 4). For all variables studied, the effects and interactions were non-significant and without effect sizes ($0.000 \leq \eta^2 \leq 0.003$).

4. Discussion

This study aimed to compare D_a, C_{Da} and, P_{tot} between two breathing patterns in the breaststroke technique: inhaling every stroke versus every two strokes. It was hypothesized that breathing every two strokes would result in lower D_a compared to breathing every stroke. The main results showed non-significant differences between hydrodynamic characteristics (v_{free}, v_{tow}, D_a, C_{Da} and P_{to}) in the two breathing patterns, even when controlling for age and velocity.

In the present study D_a values are in agreement with values previously reported (ranged between 16 N and 133 N). The literature on D_a in breaststroke swimming is scarce, primarily due to the scarcity of experimental approaches capable of measuring D_a in this swimming technique. It is important to note that no method can be considered as ideal or a gold standard and that all methods provide an estimated value of D_a. Reported values typically range from 20 N to 160 N, influenced by performance level, gender, and age (Kolmogorov et al., 1997, 2021; Xin-Feng et al., 2007). Several experimental approaches to measure the D_a have been reported (mostly in front crawl). However, results from different D_a assessment methods are inconsistent. For instance, the measuring active drag system (MAD-system) (Hollander et al., 1986), where only front crawl can be measured, and the assisted towing method at constant speed (ATM) (Alcock and Mason, 2007), revealed significantly greater mean D_a values than the VPM (Mason et al., 2013; Toussaint et al., 2004). Conversely, the Naval-Based Architecture method showed similar results to VPM at maximal velocity (Webb et al., 2011). Nevertheless, for the same mean maximum velocity, the MAD-system and ATM methods differed by 55 %, with higher values in the

Table 2
Swimmers' basic hydrodynamic characteristics swimming breaststroke inhaling every stroke cycle (Br 1/1) and every two stroke cycles (Br 1/2).

Subjects	vfree (m/s)		vtow (m/s)		Da(N)		C_{Da}(ad)		Ptot(W)	
	Br1/1	Br1/2	Br1/1	Br1/2	Br1/1	Br1/2	Br1/1	Br1/2	Br1/1	Br1/2
F1	1.04	1.03	0.97	0.96	41.98	47.03	0.69	0.80	43.83	48.45
M1	1.31	1.35	1.23	1.27	81.27	94.12	0.56	0.61	106.39	126.66
F2	1.13	1.12	1.07	1.08	79.54	105.15	0.91	1.09	89.61	117.33
M2	1.26	1.26	1.15	1.18	53.21	70.36	0.47	0.62	66.84	88.72
F3	1.02	1.02	0.95	0.94	43.82	38.23	0.63	0.55	44.57	39.07
F4	1.17	1.19	1.10	1.12	62.10	66.74	0.60	0.63	72.86	79.52
M3	1.12	1.20	1.07	1.12	82.25	59.20	0.89	0.56	92.34	71.00
M4	1.38	1.35	1.29	1.26	86.79	74.01	0.52	0.46	119.78	100.11
F5	1.07	1.13	0.99	1.02	43.06	37.17	0.52	0.41	46.23	41.87
F6	0.90	0.93	0.85	0.90	38.76	88.48	0.98	2.10	34.99	82.57
F7	1.13	1.09	0.96	0.97	20.61	28.50	0.23	0.34	23.22	31.05
F8	1.02	0.98	0.86	0.87	16.11	21.87	0.25	0.37	16.44	21.41
M5	1.18	1.13	1.05	1.08	32.01	84.10	0.38	1.08	37.72	94.74
F9	1.15	1.18	1.11	1.08	133.16	48.42	1.33	0.46	153.06	56.97
M6	0.96	0.98	0.91	0.91	62.47	41.68	1.08	0.69	59.80	40.68
Mean ± SD	1.12 ± 0.13	1.13 ± 0.13	1.04 ± 0.13	1.05 ± 0.12	58.48 ± 30.48	60.34 ± 25.39	0.67 ± 0.31	0.72 ± 0.44	67.18 ± 38.55	69.34 ± 32.38

vfree – swimming velocity while swimming freely; vtow – swimming velocity while swimming with the towed body; Da(N) – swimmer's active drag; $\mathbf{C_{Da}}$ (ad) – dimensionless coefficient of hydrodynamic force; Pto(W) – total external mechanical power.

Table 3
Comparison of the hydrodynamics swimming breaststroke every stroke cycle (Br 1/1) and every other stroke cycle (Br 1/2).

	Br 1/1	Br 1/2	T-test	p	Cl	Cohen's d
	Mean ± SD [95Cl]	Mean ± SD [95Cl]				
vfree (m/s)	1.12 ± 0.13 [1.05;1.19]	1.13 ± 0.13 [1.06;1.20]	−0.678	0.509	[-0.02, 0.01]	−0.175
vtow (m/s)	1.04 ± 0.13 [0.97;1.11]	1.05 ± 0.13 [0.98;1.12]	−2.000	0.065	[-0.02, 0.00]	−0.516
Da(N)	58.48 ± 30.48 [41.60;75.36]	60.34 ± 25.39 [46.28;74.40]	−0.222	0.828	[-19.85, 16.12]	−0.057
$\mathbf{C_{Da}}$(ad)	0.67 ± 0.31 [0.50;0.84]	0.72 ± 0.44 [0.47;0.96]	−0.418	0.682	[-0.30, 0.20]	−0.108
Pto(W)	67.18 ± 38.55 [45.83;88.53]	69.34 ± 32.38 [51.41;87.28]	−0.235	0.817	[-21.88, 17.55]	−0.061

vfree – swimming velocity while swimming freely; vtow – swimming velocity while swimming with the towed body; Da(N) – swimmer's active drag; $\mathbf{C_{Da}}$(ad) – dimensionless coefficient of hydrodynamic force; Pto(W) – total external mechanical power.

Table 4
ANCOVA test, of the hydrodynamics swimming breaststroke every stroke cycle (1/1) and every other stroke cycle (1/2), controlling the effect of age and velocity.

	Age main effect			Velocity main effect			Age x Velocity interaction		
	F	p	η^2	F	p	η^2	F	p	η^2
Da(N)	0.063	0.804	0.003	0.046	0.832	0.002	0.003	0.955	0.000
$\mathbf{C_{Da}}$ (ad)	0.001	0.972	0.000	0.377	0.545	0.015	0.008	0.931	0.000
Ptot(W)	0.007	0.933	0.000	0.034	0.854	0.001	0.076	0.785	0.003

Da(N) – swimmer's active drag; $\mathbf{C_{Da}}$(ad) – dimensionless coefficient of hydrodynamic force; Ptot(W) – total external mechanical power.

ATM (Formosa et al., 2012). These differences between experimental methods may be due to different technique and postural manipulations, as well as to the theoretical assumptions imposed when estimating hydrodynamic resistance (Sacilotto et al., 2023).

The VPM was selected for this study due to its capability to measure D_a in the breaststroke technique, being one of the few methods suitable for this purpose. This method is widely documented in the literature (Barbosa et al., 2015; Marinho et al., 2010; Kjendlie et al., 2008; Kolmogorov et al.,2021) and assumes that the swimmer performs at maximal power output throughout each trial, which is crucial for accurately calculating D_a. Kolmogorov (2023) demonstrated the reliability of the VPM, reporting a measurement error of no more than 5.4 % for key hydrodynamic parameters. This study also demonstrated that there were no significant differences in maximal power output between the two maximal trials, with and without the buoy. This indicates that the method is robust, even when accounting for potential variability in swimmer power output. Although the natural variability of each swimmer's power output was not explicitly measured in this study, the low measurement error suggests that the VPM is sufficiently reliable for this purpose. A limitation of this method is its reliance on a single maximal trial, conducted with and without a perturbation buoy. However, additional trials could introduce fatigue, potentially compromising the assumption of constant maximal power. Future studies should examine the consistency of swimmers' drag calculation across multiple trials on different days, while recognizing that daily variations in conditions may influence results.

The analysis of individual swimmers' data demonstrated that a substantial portion (40 %) of the sample experienced a decrease in D_a when swimming Br 1/2 compared to swimming Br 1/1, and some of these swimmers also achieved higher velocity. This observation suggests that for certain individuals, reducing breathing frequency may contribute to improved hydrodynamic performance in breaststroke. By breathing less frequently, these swimmers potentially minimize disruptions to their streamlined position and reduce their frontal component of drag, leading to a lower D_a value and therefore higher velocity. This aligns with the existing literature, where, for instance, in the front crawl technique results showed that not breathing through the entire 25 m trial produced shorter times, faster velocity and stroke frequency compared to higher breathing frequencies (Couto et al., 2015; Pedersen & Kjendlie, 2006). While S is treated as a constant in our calculations, it remains a crucial factor in determining D_a. In Kolgomorov́s method, the variable extracted firstly is D_a. Thereafter, to estimate C_{Da} one must input of S value (a contant). Consequently, small changes in S should be accounted into C_{Da} computation. Therefore, it is plausible that variations in D_a between the two breathing patterns could stem from subtle differences in S, despite not directly assessed. Additionally, the observed differences in P_{tot} for the same swimmer, between breathing patterns, can be attributed to changes in either D_a or swimming velocity, as expressed by the equation $P_{tot} = D_a \times v$ (Equation (3). Consequently, even small variations in D_a or velocity have the potential to significantly impact P_{tot}.

Conversely, among the swimmers, nine exhibited lower D_a values while swimming Br 1/1, with six of them also showing higher velocity values compared to swimming Br 1/2. This suggests a contrasting scenario, where breathing every stroke yields an improved hydrodynamic performance for these individuals. One possible explanation could be that these swimmers have mastered a technique that minimizes the disruption to their streamline position while breathing. For instance, they may execute a breathing motion that involves less torso extension, thereby reducing the amount of drag generated during each breath. Since D is influenced by factors such as velocity, shape, and frontal surface area (Kjendlie & Stallman, 2008), this technique allows them to a more efficient body position throughout the stroke cycle. Consequently, swimmers can achieve lower D_a values and higher velocities, even with increased breathing frequency. Additionally, it is possible that the training time devoted to adapting to the new breathing pattern was insufficient for some swimmers to fully optimize their technique. As a result, these swimmers might benefit more from the breathing pattern they have consistently used throughout their training.

Interestingly, three swimmers displayed higher D_a values while swimming Br 1/2, yet they achieved higher velocity with this pattern compared to swimming Br 1/1. The increase in both D_a and velocity among these swimmers suggests that they may have generated more power to achieve higher speeds, thereby increasing drag. This phenomenon could be attributed to the inherent drag resistance encountered by swimmers as they displace through water. As velocity increases, likewise the hydrodynamic drag also increases, following the quadratic relationship between drag and velocity (Kjendlie & Stallman, 2008): $D = \frac{1}{2} \times C_D \times \rho \times S \times v^2 (Equation 1)$. Despite the apparent detriment to D_a values resulting from reduced breathing frequency in these swimmers, the observed higher velocity may indeed be attributed to the relationship between velocity and drag. These findings highlight the need for customized approaches to optimizing swimming performance, as individual swimmers may respond differently to variations in breathing patterns and drag.

Comparing the pooled sample by paired t-tests, our analysis did not reveal significant differences in D_a, C_{Da} and, P_{tot} between the two breathing patterns. A lack of difference may be due to the fact that swimmers, when swimming Br 1/1, do not raise their torso significantly, or that swimmers maintain a similar torso elevation whether breathing every stroke or not. This phenomenon implies that a thorough kinematic analysis is required to elucidate any subtle variations in technique or performance. Furthermore, to address potential confounding factors such as age and swimming velocity, ANCOVA analysis was conducted. The results indicated that neither sex nor velocity significantly influenced the variables studied. This suggests that possible differences in hydrodynamic characteristics between breathing patterns cannot be attributed to these factors.

To our knowledge this is the first study in D_a in breathing patterns in swimming, more particularly in the breaststroke technique. A key limitation is the absence of kinematic analysis to explain the specific differences between the breathing patterns. Although we measured hydrodynamic factors like D_a and velocity, we did not assess limb kinematics. Additionally, the 25 m test may not fully capture the demands of longer races or varied breathing frequencies, limiting the applicability of our findings to competitive settings.

5. Conclusions

Our study investigated the hydrodynamic characteristics of swimmers performing two breathing patterns in the breaststroke technique. Results made possible to conclude about the coexistence of distinct responses among the swimmers, with 40 % of the sample demonstrating lower D_a while breathing every two strokes, indicating potential efficiency gains for this subgroup. Conversely, 60 % of the swimmers exhibited higher D_a values with the every-two-strokes breathing pattern compared to breathing every stroke. Interestingly, despite these variations in D_a, our analysis showed there were no significant differences in swimmer velocity between the two breathing patterns. Further examination accounting for age and velocity as potential confounding factors revealed non-significant effects and interactions, indicating that these factors did not significantly influence the observed differences in hydrodynamic characteristics.

CRediT authorship contribution statement

Miriam Alves: Writing – original draft, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Software. **Tiago M. Barbosa:** Writing – review & editing, Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization. **João Paulo Vilas-Boas:** Writing – review & editing, Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization.

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.

Acknowledgements

This research is funded by the Portuguese Foundation for Science and Technology (PhD individual grant: https://doi.org/10.54499/2021.08308.BD).

References

Alcock, A., Mason, B., 2007. Biomechanical analysis of active drag in swimming. In: Proceedings of the 25th International Symposium of Biomechanics in Sports, pp. 212–215.

Alves, F., Cunha, P., Gomes-Pereira, J., 1999. Kinematic changes with inspiratory actions in butterfly swimming. In: Keskinen, K.L., Komi, P.V., Hollander, A.P. (Eds.), Biomechanics and Medicine in Swimming VIII. University of Jyvaskyla, Finland, Jyvaskyla, pp. 9–14.

Barbosa, T.M., Morais, J.E., Marques, M.C., Silva, A.J., Marinho, D.A., Kee, Y.H., 2015. Hydrodynamic profile of young swimmers: Changes over a competitive season. Scand. J. Med. Sci. Sports 25 (2), e184–e196.

Clarys, J.P., 1975. Total resistance of selected body positions in the front crawl. Swimming II. 110–117.

Couto, J.G.M.D., Franken, M., Castro, F.A.D.S., 2015. Influence of different breathing patterns on front crawl kinematics. Revista Brasileira De Cineantropometria & Desempenho Humano 17, 82–90.

Formosa, D.P., Toussaint, H.M., Mason, B.R., Burkett, B., 2012. Comparative analysis of active drag using the MAD system and an assisted towing method in front crawl swimming. J. Appl. Biomech. 28 (6), 746–750.

Guadagnoli, M.A., Lee, T.D., 2004. Challenge point: a framework for conceptualizing the effects of various practice conditions in motor learning. J. Mot. Behav. 36 (2), 212–224.

Hahn, A., Krug, T., 1992. Application of knowledge gained from the coordination of partial movements in breaststroke and butterfly swimming for the development of technical training. Swimming Science VI 167–171.

Hollander, A.P., De Groot, G.J., van Ingen Schenau, H.M., Toussaint, H., de Best, H., Peeters, W., Meulemans, A., Schreurs, A.W., 1986. Measurement of active drag during front crawl arm stroke swimming. J. Sports Sci. 4 (1), 21–30.

Kjendlie, P.L., Stallman, R.K., 2008. Drag characteristics of competitive swimming children and adults. J. Appl. Biomech. 24 (1), 35–42.

Kolmogorov, S., 2023. Development of the technology to measure active drag of swimmers by the method of small perturbations. J. Biomech. 149, 111486.

Kolmogorov, S.V., Duplishcheva, O.A., 1992. Active drag, useful mechanical power output and hydrodynamic force coefficient in different swimming strokes at maximal velocity. J. Biomech. 25 (3), 311–318.

Kolmogorov, S.V., Rumyantseva, O.A., Gordon, B.J., Cappaert, J.M., 1997. Hydrodynamic characteristics of competitive swimmers of different genders and performance levels. J. Appl. Biomech. 13 (1), 88–97.

Kolmogorov, S., Vorontsov, A., Vilas-Boas, J.P., 2021. Metabolic Power, Active Drag, Mechanical and Propelling Efficiency of Elite Swimmers at 100 Meter Events in Different Competitive Swimming Techniques. Appl. Sci. 11 (18), 8511.

Marinho, D.A., Barbosa, T.M., Costa, M.J., Figueiredo, C., Reis, V.M., Silva, A.J., Marques, M.C., 2010. Can 8-weeks of training affect active drag in young swimmers? J. Sports Sci. Med. 9 (1), 71.

Mason, B., Kolmogorov, S., Wilson, B., Toussaint, H., Sinclair, P., Schreven, S., Hazrati, P., 2013. Comparison between active drag values estimated using both the velocity perturbation method and the AIS assisted towing method. In: ISBS-Conference Proceedings Archive.

Morais, J.E., Marques, M.C., Marinho, D.A., Silva, A.J., Barbosa, T.M., 2014. Longitudinal modeling in sports: Young swimmers' performance and biomechanics profile. Hum. Mov. Sci. 37, 111–122.

Morais, J.E., Sanders, R.H., Papic, C., Barbosa, T.M., Marinho, D.A., 2020. The influence of the frontal surface area and swim velocity variation in front crawl active drag. Med. Sci. Sports Exerc. 52 (11), 2357–2364.

Morais, J.E., Barbosa, T.M., Garrido, N.D., Cirilo-Sousa, M.S., Silva, A.J., Marinho, D.A., 2023. Agreement between different methods to measure the active drag coefficient in front-crawl swimming. J. Hum. Kinet. 86, 41.

Pedersen, T., Kjendlie, P.L., 2006. The effect of the breathing action on velocity in front crawl sprinting. Portuguese Journal of Sport. Science 6 (supl 2), 75–77.

Pendergast, D., Mollendorf, J., Zamparo, P., Termin 2nd, A., Bushnell, D., Paschke, D., 2005. The influence of drag on human locomotion in water. Undersea Hyperbaric Medicine 32 (1), 45–57.

Sacilotto, G., Sanders, R., Gonjo, T., Marinho, D., Mason, B., Naemi, R., Papic, C., 2023. "Selecting the right tool for the job" a narrative overview of experimental methods used to measure or estimate active and passive drag in competitive swimming. Sports Biomech. 1–18.

Toubekis, A.G., Adam, G.V., Douda, H.T., Antoniou, P.D., Douroundos, I.I., Tokmakidis, S.P., 2011. Repeated sprint swimming performance after low-or high-intensity active and passive recoveries. J. Strength Cond. Res. 25 (1), 109–116.

Toussaint, H.M., De Groot, G., Savelberg, H.H.C.M., Vervoorn, K., Hollander, A.P., van Ingen Schenau, G.J., 1988. Active drag related to velocity in male and female swimmers. J. Biomech. 21 (5), 435–438.

Toussaint, H.M., Roos, P.E., Kolmogorov, S., 2004. The determination of drag in front crawl swimming. J. Biomech. 37 (11), 1655–1663.

Webb, A.P., Taunton, D.J., Hudson, D.A., Forrester, A.I., Turnock, S.R., 2015. Repeatable techniques for assessing changes in passive swimming resistance. Proceedings of the

Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology 229 (2), 126–135.

Xin-Feng, W., Lian-Ze, W., Wei-Xing, Y., De-Jian, L., Xiong, S., 2007. A new device for estimating active drag in swimming at maximal velocity. J. Sports Sci. 25 (4), 375–379.

Zamparo, P., Gatta, G., Pendergast, D., Capelli, C., 2009. Active and passive drag: the role of trunk incline. Eur. J. Appl. Physiol. 106, 195–205.